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Estimating Risk from Spillways on Dams Using Condition Assessment Data

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ESTIMATING RISK FROM SPILLWAYS ON DAMS USING CONDITION ASSESSMENT DATA

Allen C. Estes
Colonel, U.S. Army

21 May 2004

June 1, 2004

To whom it may concern,

I offer the following thoughts on the research and report recently completed by COL Allen Estes for the Engineering Research and Development Center.

The US Army Corps of Engineers owns and operates a substantial inventory of Civil Works infrastructure. The difficulties of managing this inventory increase substantially as the structures age. More than 50% of the inventory is now older than the original design life. These valuable but aging structures provide an excellent opportunity to apply creative engineering thought to important questions about how to best maintain and enhance the Army' infrastructure.

Civil Works infrastructure is important to the nation's economy but also to the military warfighter. Approximately 30% of the inter-city good transport is on the navigable waterways, the Corps generates 24% of the US hydropower, and the Corps is the largest recreation provider in the US. More than one half of the Corps workforce is employed on the Civil Works side. This provides an important resource of engineering expertise that can be applied to military applications as the need arises. The rebuilding of Iraq provides the best example but there have been many others in the last 10-20 years.

COL Estes has taken Condition Indexes (CIs) developed for Civil Works structures and extended their applicability in a direction I have long thought appropriate. Design and safety evaluation of structures is becoming increasingly risk-based but it is difficult to incorporate the current condition into risk models. Proxies such as age and usage must often suffice. COL Estes has investigated this issue and developed a methodology for prioritization of repair and rehabilitation using CIs in a risk-based hierarchy. His ideas present an original alternative to more recognized risk based engineering evaluations with significantly different strengths and weaknesses that merit further consideration.

I find it to be somewhat difficult to grade this work base on the scale that was sent. COL Estes' work merits many of the descriptives listed under "A" work, particularly "new understanding" and "original." I also found the report to be well written; the charts and graphs were highly professional; and the explanations were thorough and backed up by numerical examples. COL Estes was forthright in listing both the strengths and limitations of the methodology he proposes. I have some concerns about the limitations, specifically concerning the validity of using reliability methods for condition indices and how best to describe system behavior. These concerns can only be addressed over the coming months as COL Estes, my colleagues, and I digest this research and decide how it can best be implemented by the Corps of Engineers. Because there are unresolved issues that will require further effort, I would like to assign an "A-" grade.

I have appreciated the opportunity to collaborate with COL Estes. His work provides a valuable addition to the Corps Civil Works research.

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"Those who would give up Liberty, to purchase a little temporary Safety, deserve neither Liberty nor Safety." - Ben Franklin

Estimating Risk from Spillways on Dams Using Condition Assessment Data

Chapter 1: Introduction

1.1 Background

The United States Army Corps of Engineers is responsible for maintaining and operating the Nation's navigable waterways and is the primary agency for maintaining federal flood control dams. This includes a vast amount of infrastructure that includes 270 navigation dams, 350 reservoir dams, and 238 lock chambers [Bullock and Foltz 1995]. The inland waterways which are maintained by the Corps of Engineers are used to transport 630 million tons of consumer goods every year that include petroleum, coal, construction aggregate, chemicals, grain, and mineral ores, with an annual value of $73 billion. The navigable inland waterways carry roughly 17% of the Nation's volume of intercity cargo – a significant portion of the economy [USACE 2004].

The entire inventory of navigation structures is deteriorating over time and requires billions of dollars to upgrade, maintain, and repair. Over half of the locks and dams operated by the Corps of Engineers are over 50 years old. In 2002, General Flowers [Flowers 2002] reported a critical maintenance backlog of $587 million for navigation. The Civil Works Budget for 2003 was $4.3 billion, of which $1.98 billion (roughly 46%) was allocated for General Operation and Maintenance. Within the Corps budget, navigation structures are competing with projects that involve flood control, ecosystem restoration and recreation facilities. Since the terrorist attack of 9/11, infrastructure security has become a priority. In determining the size of the Corps of Engineers budget, Congress must decide between a huge range of competing priorities that include everything from national defense and education to health care and foreign aid.

As such, maintenance dollars are scarce, will never be sufficient to cover all needs and therefore must be allocated efficiently. The Corps attempts to do this by using Principles for Improving Performance which include objective criteria, cost-benefit analyses, and a rank-order comparison of competing projects. The goal is to fund the activities that yield the greatest net benefit to society per dollar invested [OMB 2004]. Because the decisions are quantitative in nature, the Corps of Engineers uses analytical tools and methods that help determine if the benefits of a project outweigh the associated costs. For an allocated amount of money, the Corps must prioritize which structures would benefit the most from maintenance investment.

1.2 Risk-Based Analysis

In most instances, maintenance dollars should be allocated to those projects that pose the greatest risk where risk is quantified as a product of failure consequences and probability of occurrence. Similarly, in a cost-benefit analysis, the benefit is often computed as the reduced risk achieved by making a repair or rehabilitating a structure. In both cases, a probabilistic analysis is needed to quantify the probability of failure under existing and future conditions.

A major rehabilitation project, for example, typically involves a cost of over $8 million and requires a time-dependent reliability analysis as justification [USACE 1996]. This process involves defining all random variables, predicting how loads will change and the structure will deteriorate over time, and quantifying the probability of failure of the structure at various points in time. The probability of failure is the probability that the demand on the structure will exceed its capacity. These point-in-time probabilities of failure are converted to a hazard function which describes the probability of failure in a particular year given the structure has not already failed. The hazard function is applied to an event tree that incorporates the consequences of failure to define the risk to the structure. This risk is used in the cost-benefit analysis to assess the effectiveness of the proposed major rehabilitation. A similar procedure is used to perform a reliability analysis on electrical and mechanical equipment, except that the reliability is based on previous statistical performance, rather than a capacity-demand analysis.

1.3 Condition Index

At the same time, the Corps of Engineers has developed a Condition Index (CI) inspection system for the various structures it operates and maintains. A CI is a standardized snapshot assessment of the condition of a structure based on a visual inspection. The Condition Index ranges from 0 (failed) to 100 (excellent) and was developed to assist in the prioritization of nonrecurring maintenance work. CI systems have been developed for miter gates, tainter gates, embankment dams, sector gates, hydropower structures, and coastal projects such as breakwaters and jetties. While the CI is a valuable tool for comparing the relative condition of various structures, it does not offer a good measure of risk to a structure.

The Corps of Engineers is currently evaluating a procedure for calculating a CI for spillways on dams (Chouinard *et.al.* 2003). This CI procedure defines the spillway system of a dam as a hierarchical structure consisting of subsystems, components, and inspectable sub-components. The various components and sub-systems are assigned importance factors based on specific failure modes such as overtopping, failure of a gate to close, unintentional gate opening, or reservoir drawdown. The importance factors and overall condition based on component inspection results allows a condition index to be computed at every stage of the structural hierarchy.

1.4 Objective

The purpose of this report is to examine whether this CI methodology can be used to assess structural risk. Since the consequences of failure can be determined separately, the focus of this report is to examine if this condition index information can be used to compute a probability of failure for the structure. If successful, the Corps of Engineers will have a risk-based means to prioritize maintenance dollars using periodic inspection data. Furthermore, if a risk-based approach using condition indices can be developed for one structure, the results and methodology can eventually be applied to other structures as well.

1.5 Report Structure

This report consists of seven chapters. **Chapter 1** is the introduction and describes the purpose and approach to the research. **Chapter 2** examines the state of the art and the existing methods for conducting a reliability analysis and a condition index assessment of structures. The issues and challenges associated with using CI data to quantify risk are addressed. **Chapter 3** looks specifically at dam spillways. It includes a description of how they work and what is required for a reliability analysis. The CI procedure developed by Chouinard *et.al* (2003) is described. **Chapter 4** develops a general methodology for using CI ratings to quantify risk. The necessary assumptions are listed along with their implications. The methodology and specific computations are illustrated on a simple, hypothetical example problem. **Chapter 5** applies the previously described methodology to dam spillways. The Great Falls Spillway, one of the six Winnepeg River Plants managed by Manitoba Hydro, is used as an example. **Chapter 6** demonstrates how vulnerability assessment as it relates to potential terrorism could be incorporated into the process. The effect is illustrated using the hypothetical structure from Chapter 4. Finally, **Chapter 7** offers conclusions and recommendations. The strengths and weaknesses of the proposed method are discussed along with suggestions for future research.

Chapter 2: State of the Art

2.1 Risk Assessment and Reliability Analysis

Risk is the combination of failure probability and consequences. Failure occurs when a structure no longer performs as intended. In its simplest form, if the cost of a structural failure is $10,000 and the estimated probability of failure is 30%, then the expected value of the risk is $3,000. While the cost of a failure requires a number of assumptions and computations, this study focuses on determining the probability of failure. Reliability-based methods have gained an increasing acceptance in academic circles and are beginning to be acknowledged and used by engineer practitioners. Reliability methods take a probabilistic approach to designing and analyzing a structure where the result is a reliability index or a probability of failure, rather than the traditional, deterministic factor of safety. In structural design, critical factors such as loads, resistances, deterioration models, and human errors are highly random and the associated uncertainties must be quantified to adequately assess structural risk and public safety.

Reliability methods are computationally more difficult and complex than traditional deterministic methods. Such methods have only become practical as a result of the huge progress in computer methods and technology over the past two decades. In their complete form, reliability methods often involve complex convolution integrals that have no closed-form solution. Simplified methods that make first and second order approximations have been highly successful at reducing the complexity of computation while still producing accurate results. Although it often requires a large number of simulations to obtain good solutions, Monte Carlo methods have produced excellent results.

2.2 Reliability Analysis of Structures

A reliability analysis begins with a limit state equation or series of limit state equations that govern the behavior of the structure. The limit state equation is typically the same design equation that is used in a deterministic approach except the parameters of every random variable have been quantified. The yield stress for steel in a deterministic design is typically 36 *ksi*. In the reliability-based analysis, the yield stress for steel is more appropriately defined as a normally, or log-normally, distributed random variable with a mean of 40.3 *ksi* and a standard deviation of 3.9 *ksi* (Nowak 1995). A structure is considered safe or reliable if its capacity, *C*, exceeds the demand, *D*, placed on it:

$$C \geq D \quad \text{or} \quad C - D \geq 0 \quad \text{or} \quad \frac{C}{D} \geq 1 \tag{2.1}$$

The limit state surface is define as $G(X)=C\text{-}D=0$ where $\boldsymbol{X}$ is the vector of design variables in the problem. The reliability of a structure, p_s, is the probability that the structure survives or performs safely. If the capacity, *C*, and the demand, *D*, are random and the uncertainty can be quantified, then the reliability or probability of safe performance, p_s, can be expressed as:

$$p_s = P(G(\mathbf{X}) \geq 0) = P(C - D \geq 0) = \iint_{C>D} f_{C,D}(c,d)dcdd \tag{2.2}$$

where $f_C(c)$ and $f_D(d)$ are the probability density functions of C and D, respectively, and $f_{C,D}(c,d)$ is their joint probability density function. Similarly, the probability of failure, p_f, can be defined as

$$p_f = 1 - p_s \tag{2.3}$$

The computation of p_s can be quite complex depending on the number and type of uncertainties, the correlation, and the number of variables that comprise *C* and *D*.

2.2.1 Reliability Index

The most common means of communicating reliability is through a reliability index , β, which is defined as the shortest distance from the origin to the limit state surface g(**X**)=0 in standard normal space. In the case where *C* and *D* are independent, normally distributed variables, the reliability index is

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_C^2 + \sigma_D^2}} \tag{2.4}$$

where μ is the mean value and σ is the standard deviation of the variables *C* and *D*. In this case, the reliability index can be equated to the probability of failure, p_f, as follows:

$$p_f = \mathbf{F}(-\beta) \tag{2.5}$$

where Φ is the distribution function of the standard normal variate. In this case, Table 2-1 shows the relationship between reliability index and probability of failure. When the variables are not normally or log-normally distributed, or the limit state function is not linear, the reliability index cannot be directly related to the probability of failure, but it remains a highly useful means of communicating the notional level of reliability of a design.

2.2.2 Time Dependent Reliability

When attempting to make decisions about a structure over its useful life, time becomes an important variable. Loads tend to increase over time and the resistance tends to decrease as the structure deteriorates, so the overall reliability can generally be expected to decrease over time. If the load and resistance of the structure can be projected for the future, the approach for time dependent reliability is to compute the probability that a structure will perform satisfactorily for a specified period of time. Whereas probability of failure p_f is defined as the probability that an element will fail at one particular time, the cumulative distribution function $F_T(t)$ defines the probability that an element will fail at any time t :

$$F_T(t) = P(T \leq t) = p_f(t) \tag{2.6}$$

where the random variable T represents time and $t = 0$. The probability that a failure, $p_f(t)$, takes place over a time interval Δt is expressed as

$$f\ (t)\Delta t = P\{t_1 < t \leq t_1 + \Delta t\} \tag{2.7}$$

where the probability density function $f(t) = \dfrac{dF_T}{dt}$. It is assumed that the derivative exists.

The reliability is often expressed in terms of a hazard function, $H(t)$, also called the conditional failure rate. The hazard function expresses the likelihood of failure in the time interval t_1 to t_1+dt given that the failure has not already occurred prior to t_1 and can be expressed as

$$H(t) = \frac{f(t)}{p_s(t)} \tag{2.8}$$

All hazard functions must satisfy the nonnegativity requirement. Their units are typically given in failures per unit time. Large and small values of $H(t)$ indicate great and small risks, respectively (Leemis 1995). The hazard function is used in the cost-benefit analysis to justify a particular project.

2.2.3 System Reliability

A structural system may have multiple components and/or failure modes. There are many advantages gained by quantifying the inter-relationship between these components and analyzing a structure as an entire system. For example, a system analysis can reveal that some repairs are more important than others. It may also indicate that while each individual component of a structure may have adequate safety, the structure as a whole may still be unsafe.

2.2.3.1 Series Systems

If the failure of any single component will lead to the failure of the entire structure, the system is considered a series or weakest link system. If a structural system is treated as a series system of z elements, the probability of failure of the system , $p_{f,series}$,can be written as the probability of a union of events

$$p_{f,series} = P\left(\bigcup_{a=1}^{z}\{g_a(X) \leq 0\}\right) \tag{2.9}$$

where the limit state of element a is defined as $g_a(X) = 0$ and $g_a(X) < 0$ is the failure state. The correlation between failure modes must be taken into account. Consider a series system consisting of two components where the probability of failure of each individual component is $p_f = 0.01$. If the two failure modes are independent, so there is no correlation, the failure probability of the system is

$$p_{f\,series} = 1 - \prod_{a=1}^{z}(1 - p_{f_a}) = 1 - (1 - 0.01)(1 - 0.01) = 0.0199 \tag{2.10}$$

If the two events are perfectly correlated, the failure probability of the system is $p_{f,series}=$ $p_{fmax}=0.01$

2.2.3.2 Parallel Systems

A system is considered a parallel system if the system requires failures of all the components. For a parallel system, the probability of failure of the system $p_{f,parallel}$ can be written as the probability of an intersection of events

$$p_{f,parallel} = P\left(\bigcap_{a=1}^{z}\{g_a(X)\leq 0\}\right) \tag{2.11}$$

For a parallel system consisting of two components whose individual probabilities of failure are $p_f=0.01$, the system failure probability is upper bounded (first-order) by $p_{f,parallel}= p_{fmin}=0.01$ if the two failure modes are perfectly correlated and lower bounded (first-order) by

$$p_{f,parallel} = \prod_{a=1}^{z} p_{f_a} = (0.01)(0.01) = 0.0001 \tag{2.12}$$

if the two failure modes are independent. As indicated in this simplified example, there can be huge errors if correlation is neglected (Cornell 1967).

2.3 Electrical and Mechanical Reliability

Reliability analyses for electrical and mechanical equipment is more straight-forward since most electrical and mechanical components are mass produced. As such, a statistical database exists based on the actual past performance of the same components. In contrast, each civil structure is unique and there is no statistically significant sample available. For electrical and mechanical equipment, component life is divided into an initial period where failures are high due to poor workmanship or quality control, a useful life period, and a wear-out phase where failures are high due to aging and deterioration. The reliability or probability of survival at any point in time during the useful life period is computed as:

$$p_s(t) = e^{-\lambda t} \tag{2.13}$$

where t is the time period and λ is the statistical failure rate, usually found in manufacturer's data or a table of equipment. USACE (2001), for example, lists the failure rate of a butterfly valve as λ=0.29 failures per 10^6 operating hours and λ=6.88 failures per 10^6 operating hours for a DC motor. An adjusted failure rate λ' can be developed based on actual conditions where

$$\lambda' = K_1 K_2 K_3 \lambda \tag{2.14}$$

The K factors are taken from tables based on general environmental conditions, stress rating, and temperature. Given the reliability at points in time, the hazard function is calculated as described earlier. The reliability of an electrical or mechanical system is computed by creating a series-parallel system of the individual components. The electrical and mechanical analysis is generally not combined with the structural reliability analysis to obtain an overall system reliability index.

2.4 Life-Cycle Analysis

Reliability methods are often used to optimize the life-cycle cost of a structure and to make future maintenance and repair decisions. The Corps of Engineers is currently using this methodology to justify major rehabilitation of navigation structures. Padula *et.al.* (1994) explains the process in detail for the reliability of miter gates on locks to include load forecasting, deterioration modeling for corrosion and fatigue, and computation of a hazard function. Currently, the reliability is computed using Monte Carlo simulation.

Reliability methods are appropriate for maintenance and repair planning throughout the useful life of a structure. The life-cycle cost includes the costs of initial construction, preventive maintenance, repair, inspection, and expected cost of failure, among others. Life-cycle optimization must balance lifetime cost against acceptable risk. Reliability methods are best for quantifying that acceptable risk. Reliability-based condition assessment is needed to develop and update the life-cycle strategy.

2.5 Limitations of Reliability-Based Methods

The biggest drawback to reliability methods is the amount of input data needed to perform a valid analysis. The most rigorous option is to conduct tests to obtain all of the input data needed for a specific project such as strength tests of concrete, traffic surveys on a bridge, corrosion rate tests on steel, storm data analysis at the project site, etc. This is usually prohibitively expensive in terms of cost and time. Past experience and previous studies in the literature are a less costly source of data, but the results may not be applicable to the project at hand. Sensitivity analyses on the respective variables will often help identify which variables merit the most scrutiny. Unfortunately, reliability results are only as good (or bad) as the input data that support them.

In practice, the reliability analysis is based on a critical failure mode due to the complexity of the calculations. On a miter gate for example, the analysis is based on the stress on the main girder or the number of fatigue cycles. In reality, there are many distresses that could prevent a miter gate from performing as intended such as the condition of the diagonals, the anchorage arm, the motor and gear assembly, the alignment of the gate, etc. No good approach to incorporate all of these variables into a structural system for a reliability analysis has yet been developed. Russell and O'Grady (1996) introduce a risk-based life-cycle lock repair model that incorporates a system approach to analyzing a lock structure, but the probabilistic assessment is crude.

2.6 Condition Index Assessment

The best attempt to date to account for every critical aspect of structural behavior has been the condition index. A Condition Index (CI) is a rating between 0 and 100 that describes the condition of a structure at a point in time. The CI is based on a series of observations by an inspector. At the component level, the inspector classifies what he or she sees into the predefined descriptive category that best matches the observation. At the structure or system level, the CI is a composite score derived from the inspector observation using importance or weighting factors. The CI methodology was developed to prioritize and justify non-recurring operations and maintenance investments in Corps infrastructure. Table 2-2 shows the condition index rating scale, which conveniently is common to all structures. The condition of a structure is divided into seven zones that account for increased levels of deterioration.

The condition index system is developed specifically for the type of structure being evaluated. The PAVER system was originally developed for Air Force runways [Shahin *et.al.* 1976] and has been used for determining the serviceability of roads and streets [Shahin and Walther 1990]. USACE has similarly devised systems for dams, locks, and other navigation structures [Greimann *et.al.* 1990]. Since the program began in the mid-1980s, CI systems have been developed for miter gates, tainter gates, embankment dams, sector gates, hydropower structures, and coastal projects such as breakwaters and jetties. In many cases, the word descriptions that describe condition states are subjective using words like "minor, major, extensive, constant, increasing, or significant" to describe a distress. While such descriptions are the best that can be obtained in many areas, they are not easily quantified numerically. A few condition states are quantified such as the depth of erosion categorized as 0 to 1 feet, 1 to 3 feet, or greater than 3 feet (Andersen *et.al.* 1999).

2.6.1 Condition Index Benefits

The benefits of the CI system include the standardized quantification of condition, identification of specific problems in structure, establishment of a condition history for an individual structure, establishment of a database for the deterioration of a class of structures, prioritization and efficient allocation of scarce maintenance funds, and guiding less experienced inspectors on what to look for (Foltz *et.al.* 2001). A desired benefit is to use the Condition Indices in risk analysis and reliability. Foltz *et.al.* (2001) discusses the use of CIs in risk analysis, as an input to reliability, and as an approximation of reliability. They concluded that since CIs do not examine either the load or the resistance of a structure, it is not possible for CI data to provide a direct measure of reliability.

2.6.2 Potential Condition Index Uses

The CIs focus on observable deviations from a desired condition. The subcomponent observations, if they are relevant and sufficiently detailed, could be used to update or enhance the reliability analysis. Estes *et.al.* (2004) concluded that CI data could not be used to compute reliability but illustrated how quantified CI data could be used to update the time dependent reliability analysis on a miter gate. Mlaker (1994) and Ayyub *et.al.* (1996) treated the condition index ratings as the random variable to compute reliability of hydropower power equipment. The study concluded that the database of data on hydropower equipment was too sparse to make valid conclusions, but the technique showed promise if sufficient data were available.

Because CIs are based on structural behavior and response, they may offer an approximation of reliability. If so, the CIs could offer a low cost alternative to reliability studies that are complex and expensive and can only be justified for large projects. A low cost approximate approach would allow a risk-based analysis for smaller, less expensive projects than can now be justified.

2.7 An Analogy

The difference between the traditional reliability analysis and the condition index may best be described using an automobile as an analogy. A reliability analysis of an automobile might pick the most critical failure mode such as the performance of the engine. The capacity is the horsepower provided by the engine. The demand would be the horsepower needed to get the fully loaded automobile over the steepest hill that it is likely to encounter. The engine will degrade over time as it ages and wears. The probability of failure is the probability that the demand on the engine would exceed its capacity. When that probability becomes too high as determined by an economic analysis, the engine or the entire automobile is replaced.

In reality, nobody replaces an automobile using that logic. An automobile is a complex system consisting of a drive train, electrical system, body, fuel system, and accessories. For most, a replacement decision is based on a complex combination of variables such engine miles, tire wear, body rust, inoperable radio, old alternator, and worn brake pads. A condition index for the automobile would be derived from inspecting the car for all relevant variables such battery age, corrosion, shock absorber damping, engine compression, steering tightness, etc. Based on the relative importance of each of these observations, a general CI for the automobile system is created. As a transmission is replaced or new tires are purchased, the CI for those components would improve substantially and the CI for the automobile would improve relative to the importance of those components and thus, the car is less likely to need replacement.

If an individual owned a fleet of automobiles, that system CI would be very helpful in deciding which cars to replace and which would benefit most from an overhaul. If that CI data was probabilistic in nature and failure was defined by the condition at which components or systems are replaced, then a risk assessment would be possible. That is the approach this study will take.

2.8 Approach of the Study

This study concludes that there is no way to use condition index data to replace the traditional reliability analysis for a structure. They are too dissimilar and serve two different purposes. It may be possible to transform the condition index system which is deterministic in nature into a probabilistic analysis. The result would allow the same stochastic techniques involving probability of failure and hazard functions to be used in a cost-benefit analysis. This report will propose such an approach by treating the condition index as a random variable, making initial assumptions that would eventually be modified over time as a database is established, and using existing condition state definitions so that current methods and accumulated data remain valid.

Table 2-1: Relationship between Reliability Index and Probability of Failure for Normally Distributed Variables and Linear Limit State Functions

Reliability Index (β)	Probability of Failure (p_f)
0.0	0.5000
1.0	0.1587
2.0	0.02275
3.0	0.00135
4.0	0.0000316
5.0	0.000000286

Table 2-2: Condition Index Rating Scale for Inspected Structures (Greimann *et.al.* 1990)

CI Value	Condition Description	Zone	Action
85-100	Excellent : no noticeable defects, some aging or wear visible	1	Immediate action not required
70-84	Very Good: Only minor deterioration or defects evident		
55-69	Good: Some deterioration or defects evident, function not impaired	2	Economic analysis of repair alternatives recommended to determine appropriate maintenance action
40-54	Fair: Moderate deterioration; function is still adequate		
25-39	Poor: Serious deterioration in at least some portions of the structure, function inadequate	3	Detailed evaluation required to determine the need for repair, rehabilitation or reconstruction, safety evaluation required
10-24	Very Poor: Extensive deterioration, barely functional		
0-10	Failed: General failure or failure of a major component; no longer functional		

Chapter 3: Spillways on Dams

Since the specific structure for this report is spillways on dams, this chapter will discuss how a spillway works, what is required for a reliability analysis, and the details of the CI procedure developed by Chouinard *et.al* [2003].

3.1 Spillway Gates

The purpose of a spillway is to control the flow of water through a dam and convey the water from the reservoir to the tail water for all discharges up to design flood level (USACE 1990). The flow of water is controlled by gates which raise and lower to permit the passage of water. The most common gates on spillway crests and navigation locks are vertical lift (or roller gates) that are lifted with a hoist or a crane and tainter gates which are radial in shape and rotate about a trunnion pin that is anchored to the piers. Figure 3-1 (PBS 2004) shows a vertical lift gate failing on the Folsom dam. Failure 3-2 (Providence 2004) shows the Fox Point Hurricane Barrier dam with a series of tainter gates. Both gate systems consist of the gate, a supporting structure, a lifting device in the form of a crane or a motor, cables, gears, and electrical power.

Tainter gates tend to have lower maintenance, do not require a tower to house mechanical equipment, are less susceptible to fatigue, and are more economical. The radial shape provides an efficient transfer of load through the trunnion, allowing for a lower hoist capacity. No gate slots are required and tainter gates have a fast operating speed (USACE, 2000). The advantages of roller gates are a shorter length of spillway pier required, ease of fabrication, reduced erection time, and a simpler design of supports due to the single direction lifting load. Because both examples cited in Chouinard *et.al.* (2003) are both vertical lift gates, this study will focus on those structures.

Vertical lift gates rely on horizontally-framed girders as their main support members which reinforce a thin metal sheet that forms the skin plate. Intercoastals provide intermediate support in the vertical direction. Vertical lift gates may also be formed as trusses or tied arches. Wheels, revolving around a fixed axis, are attached to the ends of the gate. The wheels roll in a prefabricated slot or on rails mounted in a concrete slot as the gate is raised and lowered. A tractor, slide or stoney may be used instead of fixed wheels. The gate is lifted using an electric motor, cable drum hoist, hydraulic cylinders, or a crane (USACE 1997).

3.2 Reliability Analysis

The spillway gate is expected to withstand various loads that include hydrostatic, hydrodynamic, gravity, equipment, impact, earthquake, downpull, thermal, and wind loads. These loads all have uncertainties associated with them as defined by the random variables that describe them. A reasonable combination of these loads is considered and they effect the structure in terms of member stresses, deformations, vibrations, fatigue, etc. which becomes the demand on the structure. The spillway gate is designed with a certain capacity to resist these forces. There are uncertainties associated with the strength of the material, the dimensions of the cross-section, and the theoretical model that are also quantified as random variables. The probability of failure is the probability that demand on the structure will exceed its capacity – probably in terms of the stress on the horizontal girders. Deformations and vibrations are typically considered serviceability criteria and not as critical as the strength-based stress computations.

In a time-dependent reliability analysis, a model and its quantified uncertainty are needed to predict how the structure will deteriorate over time through such mechanisms as section loss due to corrosion. The probability of failure over time leads to the hazard function as described in the previous chapter.

For the vertical lift gates, which are subjected to repeated cyclic loading, fatigue may be the critical failure mode. For fatigue, the reliability is based on critical welded connections on downstream bracing members that are connected to the downstream flange of the horizontal girders. The applied stress range, number of loading cycles and the magnitude of the stress concentrations are critical considerations. The forecasting of the load cycles and their magnitudes provides the time-dependent analysis.

3.3 Condition Index Methodology

Chouinard *et.al.* (2003) developed a condition assessment methodology for dam spillways using condition index ratings. Dam safety with respect to the failure modes of overtopping during a design flood, overtopping during load rejection, unintentional opening of the gate, failure to close the gate, and reservoir drawdown were included. The spillway was described as a seven level hierarchy as shown in Figure 3-3. Level 7, the lowest structural level, consists of individual components (shown in light blue) where an inspector provides a rating corresponding to a descriptive table. Table 3-1, for example, shows the table for the Hoist Brake, a component of the Force Transmission system. A word description of the component function is provided along with a description of both excellent and failed behavior. The inspector observes the brake hoist and relates his or her observations to the categories described in the table. A range of CI scores are provided for each category. Of the 70 component condition tables in the study, all are based on word description rather than quantitative data.

There is no guidance as to whether the inspector chooses the highest, lowest, or some average score for the rating. Andersen *et.al.* (1999) which uses these same component tables, states that the CIs are subjective and appears to leave it to the individual inspector to choose an appropriate value. If there are several condition ratings that comprise a component, the component CI is the lowest rating of the indicator group.

The higher level CI scores for sub-systems, systems, and eventually the structure (shown in yellow in Fig. 3-3) are derived from the component CI scores and the importance values from the previous level. The importance factors (I) are elicited from expert opinion and the sum of the importance factors at any given level is equal to 1.0. If the lower level elements are in series, meaning that the system fails if any element in it fails, then the CI for the next higher level is:

$$CI_{level_{i-1}} = \sum_{j=1}^{n} I_j CI_{j,level_i} \qquad (3.1)$$

where there are j elements in level i. If the lower level elements are in parallel, where all elements must fail for the system to fail, the CI for the system is:

$$CI_{level_{i-1}} = \frac{\sqrt{\sum_{j=1}^{n} (I_{j,level_i} CI_j)^2}}{\sqrt{\sum_{j=1}^{n} I^2_{j,level_i}}} \tag{3.2}$$

This methodology provides a deterministic CI rating at every structural level that can ultimately be traced back to inspectable components. The analysis includes a number of relevant variables such as the ability to gather information, make decisions, and gain access, which are not traditionally included in a structural assessment. The importance factors and CI ratings are then use to compute priority rankings for maintenance of the various components. Chouinard *et.al* (2003) uses the Paugan (Hydro-Quebec) and Great Falls (Manitoba Hydro) as illustrative examples.

3.4 Condition Index and Risk Assessment

While this CI methodology for spillways incorporates every relevant aspect of performance from river flow measurements and emergency generators to lifting devices and gear assemblies, the information could not be used to compute the probability of failure of the spillway in the traditional sense. There is no information that helps compute stresses in members or loads over time. The information that indicates corrosion or a fatigue crack is confined to a single component table (C.66: Gate Structure) and the information is not sufficiently quantified to be useful. Similarly, since the reliability of electrical and mechanical components is based operating hours and defined environment, there is no information in the CI results that would be helpful. It simply reinforces that traditional reliability analysis and condition index ratings are too different in their purpose and scope to be interchangeable. A reliability analysis could never effectively incorporate as many variables as Chouinard (2003) considers in the assessment of spillways; the analysis would be too complex.

One alternative is to make the CI process probabilistic using the condition index as the random variable. A risk analysis is then possible relative to failure as defined within the CI system. While it is not a replacement for a traditional reliability analysis and has certain limitations, it provides some capabilities that do not exist within the current deterministic CI methods. The proposed methodology is described and illustrated in the next chapter using a simple hypothetical structure and then in the following chapter using the data and structure from the Great Falls spillway.

Table 3.1: Component Condition Table for the Hoist Brake – Part of the Force Transmission System

Hoist Brake									
Function	To arrest motion of gate and hold gate in any position								
Excellent	Can arrest motion at any position, not seized								
Failed	Cannot arrest motion at any position, seizing of brake								
Indicator	0-9	10-24	25-39	40-54	55-69	70-84	85-100	Score	Comments
Can arrest motion at any position, not seized							x		
Limited slippage without impacting operation; no slip but vibration				x	x	x			
Limited slippage that impacts operation		x	x						
Continuous slippage, seizing of brake	x								

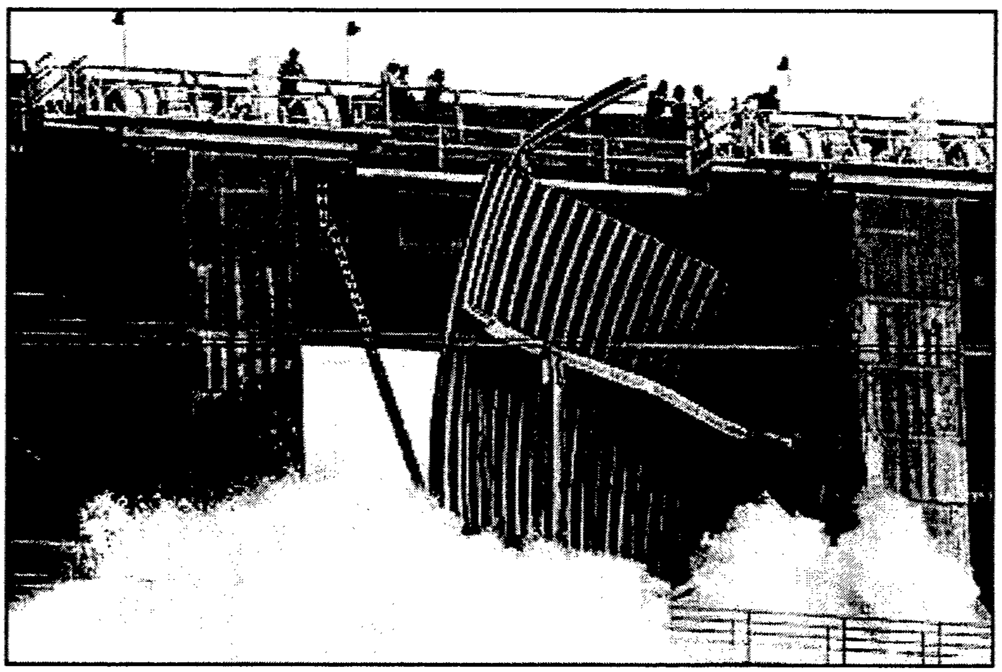

Figure 3.1: Photo of the Failure of the Vertical Gate Spillway on the Folsom Dam (PBS, 2004)

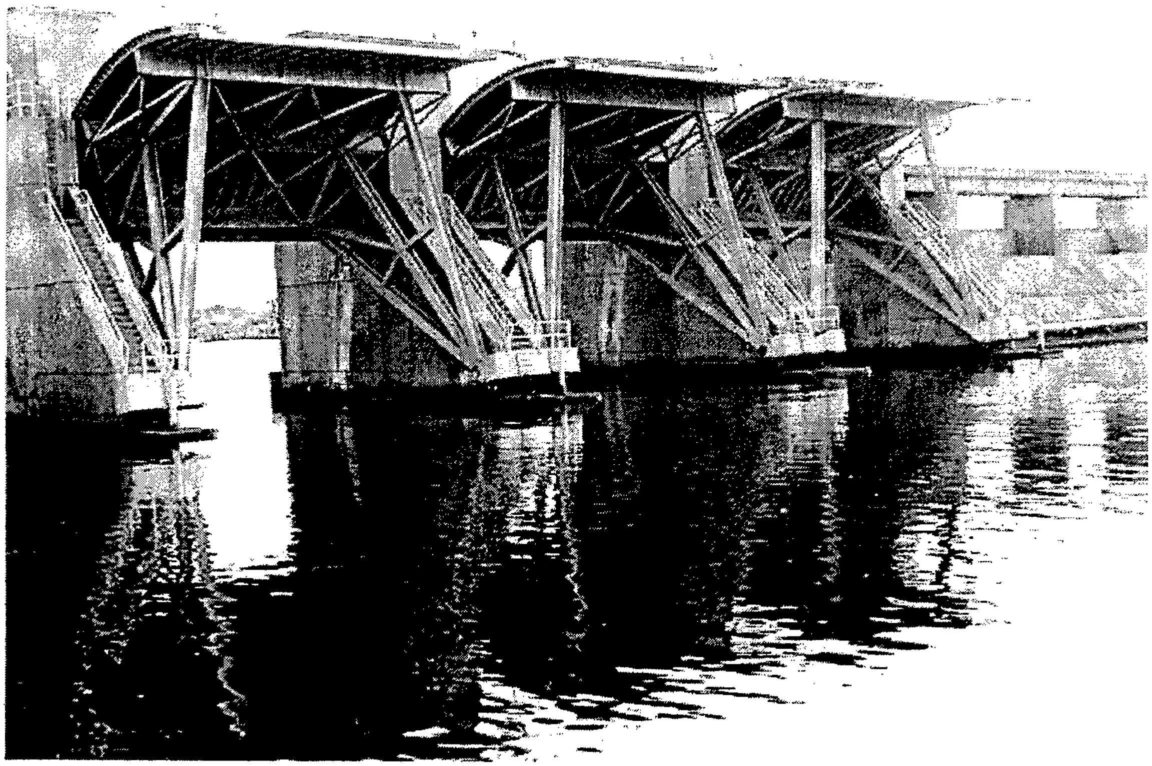

Figure 3.2: Photo of the Tainter Gates on the Fox Point Hurricane Barrier Dam
(Providence, 2004)

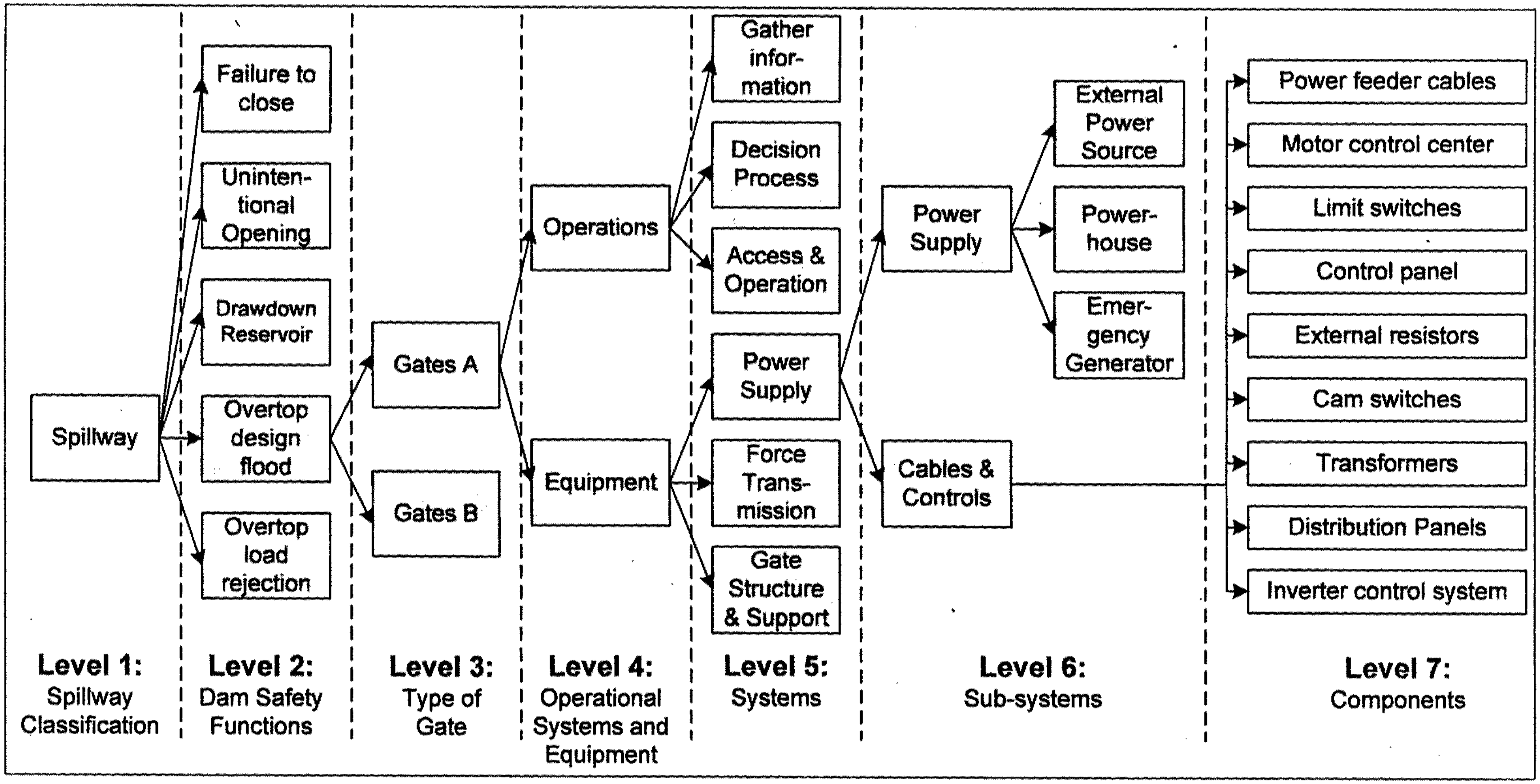

Figure 3.3: Hierarchy of Spillway System for Dams (Chouinard *et.al.* 2003)

Chapter 4: Probabilistic Condition Index Methodology

4.1 Condition Index as Random Variable

This chapter proposes a probabilistic approach to the condition index rating system where the CI is the random variable. The approach will require a number of assumptions, the reasonableness of which can be debated and modified as acquired data provides better information. With the CI as the random variable, the probability of failure is

$$p_f = P(CI_{actual} \leq CI_{failure}) \tag{4.1}$$

Initially, it is assumed that the CIs are normally distributed and independent. The analysis will be simpler and the level of accuracy attained with the approach does not justify the additional complexity of considering other distribution types or correlation between variables.

4.2 Assumptions

The parameters (mean value and standard deviation) of the actual condition index CI_{actual} will be determined by the component condition table and the confidence in the inspector to correctly assign the correct condition state to an inspected component. In this study, it is assumed that the inspector will classify the structure correctly 95% of the time, although some other reasonable values (90%, 80%) could be chosen. Factors such as inspector experience, quality assurance spot checks, training programs, formal certification, periodic meetings, and published guidance should be considered in choosing this value (Estes and Frangopol, 2003). It is assumed that the 5% inspector error is equally distributed on the high and low sides.

When an inspector assigns a condition state, there is a range of values that can be quite large. To be conservative, it is assumed that the mean value of the CI is at the center of the range when the condition state is first identified. If the condition state range is from 70 – 84, for example, the mean value would be CI=77 at the first inspection where the structure enters that condition state as shown in Fig. 4-1. Based on the assumed inspector qualifications, the probability of obtaining a value of CI<84 when the structure is actually in this condition state is 97.5% or 0.975. The standard deviation σ can be computed as:

$$
\begin{aligned}
&P(CI \leq 84) = 0.975 = \Phi(\frac{CI-\mu}{\sigma}) = \Phi(\frac{84-77}{\sigma}) \\
&\sigma = \frac{(84-77)}{\Phi^{-1}(0.975)} = \frac{(84-77)}{1.96} = 3.57
\end{aligned}
\tag{4.2}
$$

where Φ is the standard normal variate whose value can be found in the standard normal distribution tables and μ is the mean value of the condition state.

The structure is assumed to transition linearly through the condition state. The design life of the structure initially dictates how long a structure is expected to remain in a specific condition state. The mean value will shift linearly toward the lower end of the condition state over time as shown in Fig. 4.1. The standard deviation remains unchanged. If a structure remains in a condition state longer that anticipated, the mean value of the CI will remain at the lowest value until an inspection reveals that the structure has entered a different condition state. In the example above, the mean value would remain at CI=70. Greimann *et.al.* (1990) attempted to model condition index deterioration using an exponential function and Ayyub *et.al.* (1996) modeled it based on the sparse data collected. If the linear assumption is not correct, the actual inspection data will allow the model to be updated to reflect actual structural behavior as will be shown with an example in this chapter. In the absence of any data, a linear CI deterioration assumption seems reasonable.

4.3 Failure

Failure occurs when a structure no longer performs as intended. It is assumed that failure is associated with some sort of repair, rehabilitation or reconstruction. Therefore any modifications or adjustments to the failure definition can be based on the historical record of repair actions. The initial assumption of $CI_{failure}$ is N[25, 12.75] which indicates a normally distributed variable with a mean value of $CI=25$ and a standard deviation of $\sigma=12.75$. The assumption is based on the condition index definition shown in Table 2.2, where replacement occurs in the CI range of 0 – 40. From the description, it appears that a small number of repairs will occur in the 40-54 range where there is moderate deterioration. Similarly, a responsible manager of structures will not wait until a structure no longer functions (CI range 0-9) to make a repair in most cases. Greimann et.al. (1990) used CI=40 as the indicator of a potentially hazardous situation when developing a CI methodology for miter gates. Fig. 4.2 shows the $CI_{failure}$ distribution and the assumed percentage of replacements that would occur within the CI ranges. This quantification of failure will be used throughout the study.

4.4 System Condition Index

Higher level CIs for subsystems, systems and entire structures will also be probabilistic. Fig. 4.3 shows the simplest possible series system and parallel system, each consisting of two components, A and B. Component A has $CI_{actual} = N[85, 5]$ with an importance factor I=0.3, while Component B has $CI_{actual} = N[45, 20]$ with an importance factor I=0.7. For the series system, the mean value of the CI_{system} is computed using Eqn. 3.1 as

$$CI_{System} = \sum_{j=1}^{n} I_j CI_j = I_A CI_A + I_B CI_B = (0.3)(85) + (0.7)(45) = 57 \tag{4.3}$$

Because the equation is linear and the variables CI_A and CI_B are independent and normal variates, the standard deviation of the system condition index $\sigma_{CI\,system}$ is (Ang and Tang, 1975)

$$\sigma_{CI_{System}} = \sqrt{\sum_{j=1}^{n} I_j^2 \sigma_j^2} = \sqrt{I_A^2 \sigma_A^2 + I_B^2 \sigma_B^2} = \sqrt{(0.3)^2(5)^2 + (0.7)^2(20)^2} = 14.08 \tag{4.4}$$

The mean value of the parallel system condition index, CI_{system} is computed using Eqn. 3.2 as

$$CI_{System} = \frac{\sqrt{\sum_{j=1}^{n} (I_j CI_j)^2}}{\sqrt{\sum_{j=1}^{n} I_j^2}} = \frac{\sqrt{I_A^2 CI_A^2 + I_B^2 CI_B^2}}{\sqrt{I_A^2 + I_B^2}} = \frac{\sqrt{(0.3)^2(85)^2 + (0.7)^2(45)^2}}{\sqrt{(0.3)^2 + (0.7)^2}} = 53.2 \tag{4.5}$$

A reasonable first order approximation of the standard deviation of the system condition index $\sigma_{CI\,system}$ is (Ang and Tang, 1975)

$$\sigma_{CI_{System}} = \sqrt{\sum_{j=1}^{n}\left(\frac{\partial CI_{System}}{\partial CI_j}\right)^2 \sigma_{CI_j}^2} = \sqrt{\frac{\sigma_A^2 I_A^4 CI_A^2 + \sigma_B^2 I_B^4 CI_B^2}{(I_A^2 + I_B^2)(CI_A^2 I_A^2 + CI_B^2 I_B^2)}}$$

$$= \sqrt{\frac{(5)^2(0.3)^4(85)^2 + (20)^2(0.7)^4(45)^2}{((0.3)^2 + (0.7)^2)((85)^2(0.3)^2 + (45)^2(0.7)^2}} = 14.34 \tag{4.6}$$

Appendix A discusses the significance of these equations further. These equations provide the probabilistic parameters of the CI at successively higher levels.

4.5 Example Structure

The methodology is illustrated on a simple hypothetical structure shown in Fig. 4.4. The structure consists of three parallel components (A1, A2, and A3) in series with components B and C. The components (in blue) are inspected and given a CI rating based on condition tables. Components A1, A2, and A3 form sub-system A. The structure is comprised of sub-system A and component B and C. The importance factors at each level are shown in Fig. 4.4(b).

Figure 4.5 shows the condition tables and the distributions they represent for component A1, A2, and A3. The condition evaluation for component A was divided into four condition states (CS) with ranges as indicated. The condition index range for CS1 was 70 – 100 which indicates a mean value of CI = 85 when the condition state is first entered. The standard deviation for CS1 is

$$\sigma_{CS1} = \frac{(100-85)}{\Phi^{-1}(0.975)} = \frac{(100-85)}{1.96} = 7.65 \tag{4.7}$$

The parameters for the other condition states were computed in a similar manner. The distributions for the four condition states when the condition states are first entered are shown in Fig. 4.5(b) along with the distribution for failure. The probability of failure of a component will be the likelihood of the actual condition index being less than the defined failure condition index. Figures 4.6 and 4.7 show the condition tables and the resulting distributions for components B and C, respectively. Component B was divided into seven condition states, while Component C had only three. The analysis will be most effective when a component can be divided into more discrete, clearly defined categories, but this is clearly not possible for all components.

4.5 Condition Index over Time

The structure and its components are assumed to have a 50 year design life. With a linear transition of condition states, the structure should reach the zone 2 and zone 3 ($CI = 40$) dividing line (see Table 2.2) after 50 years. The components A, B, and C should pass through 1.67, 4, and 1.33 condition states, respectively, during this period based on the condition tables in Figures 4.5 through 4.7. Figure 4.8 illustrates the predicted condition state transition for components A, B, and C assuming that the structure is inspected every two years. The data points are the mean CI values at points in time. Components A and C show a steep drop from CS1 to CS2 during the first 50 years of design life. Component B shows more gentle drops as the component passed through CS1 through CS4 during the same period, which reflects the greater gradation of condition states.

Based on the condition state transition, the mean CI for component A at years 2 and 4 is equal to

$$CI_{A,Year2} = 85 - \frac{(85-70)}{(\frac{50}{1.67}-1)(2)} = 84.0 \qquad CI_{A,Year4} = 85 - \frac{(85-70)}{(\frac{50}{1.67}-1)(4)} = 82.9 \quad (4.8)$$

Similarly, the mean CI for component B at year 2 is

$$CI_{B,Year2} = 92.5 - \frac{(92.5-85)}{(\frac{50}{4}-1)(2)} = 91.2 \quad (4.9)$$

The condition state transition proceeds in this manner until the component passes to the next lower condition state where the mean CI is the midpoint of the new condition state.

The mean CI of the entire structure is computed using equation 2.1 for a series system. Because components A1, A2, and A3 are identical in their performance, the mean CI for sub-system A is identical to its components. At the time, t=0 years, when the structure is first placed into service, the mean value and standard deviation of the system structure are (Eqs. 3.1 and 3.2):

$$\begin{aligned} CI_{System,Year0} &= (0.2)(85) + (0.6)(92.5) + (0.2)(85) = 89.5 \\ \sigma_{System,Year0} &= \sqrt{(0.2)^2(7.65)^2 + (0.6)^2(3.83)^2 + (0.2)^2(7.65)^2} = 3.16 \end{aligned} \quad (4.10)$$

By year 2, the mean value of the system is shown below and the standard deviation does not change.

$$CI_{System,Year2} = (0.2)(84.0) + (0.6)(91.2) + (0.2)(84.2) = 88.3 \quad (4.11)$$

The mean value of the system CI is also shown in Figure 4.8. The system CI follows closely with component B because the importance factor was 0.6 for that component which was weighted three times as great as the other two components. If the importance factors changed, the system CI curve would reflect that.

4.6 Risk Analysis Using Condition Indices

Because the CIs have been defined in probabilistic terms, a risk analysis is possible relative to the CI definition of failure. Because the variables are normally distributed and independent, the reliability index is computed using Eq. 2.4. The reliability index for component A and for the system at year 2, for example, is computed as:

$$\begin{aligned}
\beta_{A,Year2} &= \frac{CI_{Actual} - CI_{Failure}}{\sqrt{\sigma^2_{Actual} + \sigma^2_{Failure}}} = \frac{84-25}{\sqrt{(7.65)^2 + (12.5)^2}} = 3.96 \\
\beta_{System,Year2} &= \frac{88.3-25}{\sqrt{(3.16)^2 + (12.5)^2}} = 4.82
\end{aligned} \tag{4.12}$$

Figure 4.9 shows the reliability index β for components A, B, and C and for the structure. Not surprisingly, the graphs look very similar to the mean CI values shown in Figure 4.8 over the same 70 year time period. Figure 4.10 shows the probability of failure over this period for the components and structure. The probability of failure for component A and the system at year 2 are computed using Eq. 2.5.

$$\begin{aligned}
p_{f,A,Year2} &= \Phi(-\beta) = \Phi(-3.96) = 1 - \Phi(3.96) = 1 - 0.999963 = 0.000037 \\
p_{f,System,Year2} &= \Phi(-4.82) = 7.15(10)^{-7}
\end{aligned} \tag{4.13}$$

The system probability of failure is fit to a Weibull distribution to provide a smooth curve. The hazard function is obtained using Eq. 2.8. Figure 4.10 shows for example that the probabilities of failure of the system for years 40, 42, and 44 is:

$$p_{f,System,Year40} = 0.1076 \qquad p_{f,System,Year42} = 0.1263 \qquad p_{f,System,Year44} = 0.1473 \quad (4.14)$$

Eq. 2.3 shows that the probability of survival is:

$$p_{s,System,Year40} = 1 - 0.1076 = 0.8924 \qquad p_{s,System,Year42} = 0.8737 \qquad p_{s,System,Year44} = 0.8527 \quad (4.15)$$

The hazard function for years 42 and 44 is computed as:

$$\begin{aligned} f(t)_{System,Year42} &= \frac{dF_T}{dt} = \frac{(0.1263 - 0.1075)}{42 - 40} = 0.009389 \\ H(t)_{System,Year42} &= \frac{f(t)}{p_s(t)} = \frac{0.009389}{0.8737} = 0.01075 \\ f(t)_{System,Year44} &= \frac{(0.1473 - 0.1263)}{44 - 42} = 0.01047 \\ H(t)_{System,Year44} &= \frac{0.01047}{0.8527} = 0.01228 \end{aligned} \quad (4.16)$$

This indicates that if the structure has not already failed by year 42, the likelihood of the structure needing replacement in the next year is 0.01075. Figure 4.11 shows the hazard function for the system over a 70 year period. Because the probability of failure jumps when condition states change the hazard curve is not smooth and shows spikes. Using real data, the numerical differentiation will almost never produce a smooth curve. A best-fit Weibull distribution is fit through the data. The Weibull distribution requires two-parameters γ and θ such that best fit hazard function through the data is express as [Padula et.al. 1994]:

$$h(t) = \frac{\gamma}{\theta}\left(\frac{t}{\theta}\right)^{\gamma-1} \quad (4.17)$$

The parameters are estimated through linear regression analysis. The data for time t and reliability p_s over the 76 year period is converted to x and y data using the equations:

$$x_{Year42} = \ln(t) = \ln(42) = 3.738$$
$$y_{Year42} = \ln(\ln\frac{1}{p_s}) = \ln(\ln(\frac{1}{0.8737})) = -2.002 \tag{4.18}$$

The x-y data is fitted to the linear equation

$$y = ax + b \tag{4.19}$$

Using the data for the 70 year period, regression analysis showed that $a=-22.67$ and $b=5.483$. The parameters γ and θ are computed as:

$$\gamma = b = 5.483$$
$$\theta = \frac{1}{e^{(\frac{a}{b})}} = \frac{1}{e^{(\frac{-22.67}{5.483})}} = 62.50 \tag{4.20}$$

The hazard functions for the best fit curve for years 42 and 44 are:

$$h(t)_{Weibull,year42} = \frac{5.483}{62.5}(\frac{42}{62.5})^{(5.483-1)} = 0.01477$$
$$h(t)_{Weibell,year44} = \frac{5.483}{62.5}(\frac{44}{62.5})^{(5.483-1)} = 0.01819 \tag{4.21}$$

Figure 4.11 shows the best-fit hazard function for the entire time period.

Consider the failure consequences of the structure as shown in Figure 4.12. There is a 30% chance that if the structure fails, the consequences will be slight and the cost will be only \$200,000. At the other extreme, there is a 5% chance that the failure will be catastrophic and cost \$3.6 million. The expected cost of failure based on the event tree is:

$$E(Cost)_{failure} = (0.30)(\$200,000) + (0.50)(\$450,000) + (0.15)(\$1,200,000) + (0.05)(\$3,600,000) = \$645,000 \tag{4.22}$$

At year 42, the expected annual cost of keeping the structure in service, assuming no maintenance cost, is

$$E(Cost)_{Year42} = \$645{,}000(0.01477) + \$0(1 - 0.01477) = \$9{,}527 \tag{4.23}$$

The present value cost C_{pv} of a new structure at year 42 is \$200,000 with an anticipated design life of 50 years. Assuming a discount rate of 6%, the annual cost over the 50 year life is

$$C_{annual} = \frac{C_{pv} r(1+r)^n}{(1+r)^n - 1} = \frac{\$200{,}000(0.06)(1+0.06)^{50}}{(1+0.06)^{50} - 1} = \$12{,}689 \tag{4.24}$$

The new structure is not justified at year 42 because the annual cost of \$12,689 exceeds the annual benefit of \$9,527 provided by a new structure.

Figures 4.8 through 4.12 reflect that a risk-based cost-benefit analysis is possible using CI data. The inspection results in this example reflect a structure that performed as predicted and all of the assumptions are valid. Admittedly, the assumptions are not based on data, but as time passes and the CI data for a structure becomes available through actual inspection, the assumptions can be modified and the life cycle maintenance plan can be updated. The advantage is that the data needed for the analysis is exactly the data that is being inspected.

4.7 Actual vs. Expected Structural Performance

The next examples illustrate what occurs if the structure does not behave as predicted or if the assumptions prove invalid. Figure 4.13 shows the results for a structure where every component is deteriorating at twice the expected rate. The changes in condition state for the components show a steeper drop than in Figure 4.8. The actual CI for the system is still a factor of the importance and condition state of it constituent components. Figure 4.13 compares the actual structure CI to the predicted structure CI over forty years. The life of the actual structure will be 20-30 years, rather than the design life of 50 years, but the inspection results show within the first decade of life that the structure is behaving differently than expected and a revised life-cycle maintenance plan can be developed. The same analysis described earlier is conducted for the more rapidly deteriorating structure. Figure 4.14 shows the actual hazard function and best-fit Weibull hazard function for the more rapidly deteriorating structure.

Similarly, Figure 4.15 shows the results for a structure where every component is deteriorating at half the expected rate. The CI values for the components flatten out as the structure behaves better than expected and the mean CI remains at the lowest value in the condition state until an inspector finds that it has deteriorated to the next condition state. The actual structure CI is compared to the original prediction and the expected life of the actual structure is around 75 years, rather than 50. This trend is evident by year 20, so there is plenty of opportunity to defer repair and rehabilitation to a higher priority project. Figure 4.16 shows the actual data and best-fit hazard functions for the less deteriorated structure.

Figure 4.17 overlays the three hazard functions from Figures 4.11, 4.14, and 4.16 for the original structure, the structure deteriorating at double the expected rate, and the structure at half the deterioration rate. If a cost-benefit analysis was conducted at year

30, the hazard function values h(30) would be 0.00327, 0.0501, and 0.000179, respectively. They all differ by an order of magnitude and would make a huge difference in the economic analysis. It underscores that the initial assumptions may be drastically wrong, but the periodic inspection and updating, allows for significant correction over time.

4.8 Effect of Repairs over Time

Figure 4.18 considers the case where components A1 and B are deteriorating at half the expected rate, A3 and C at double the expected rate, and A2 at the expected rate. The mean CI rating for the actual structure and the predicted structure are both shown. Component C completely fails at year 40, but the structure CI is only moderately affected because the importance factor of component C was only $I=0.2$ and Component B, which is behaving better than expected, has an importance factor of $I=0.6$. At Year 40, Component C is replaced and its CI reflects the new condition by Year 42. The CI of the system improves somewhat as a result, indicating a better condition of the overall structure. At Year 46, the mean CI of System A rises from 51 to 67, but not all the way back to its new condition of $CI = 85$.

Figure 4.19 shows the individual components A1, A2, and A3 of the parallel subsystem A. At Year 46, component A3 needs to be replaced and its CI returns to its original value of CI=85. Because components A1 and A2 are still performing well, they are not replaced. Thus, the CI of system A improves, but not back to its original condition, after the replacement of A3. Because System A is a parallel system, Equations 3.2 and 4.6 were used to compute the mean CI and standard deviation of the system.

4.9 Alternative System Approaches

The treatment of a structure as a system is controversial because there are several alternative approaches that could be taken:

1. The approach taken by Chouinard (2003) and this report treats the higher level CI as the overall condition of the structure based on the component CIs and their relative importance. This allows entire structures competing for the same resources to be compared at a higher level. Returning to the automobile analogy, if a manager has a fleet of cars, one car might be ten years old, have experienced a series of electrical problems, and never had the brakes replaced. A second car is eight years old and is showing signs of body rust and a faltering transmission. A system CI would be helpful in assessing which car would benefit most from scarce maintenance dollars. The probabilistic analysis would help determine if either project could be justified economically.

2. A second approach is to compute the system reliability using equations 2.10 and 2.12 for series and parallel systems, respectively. This traditional reliability approach should produce a series system CI that would be lower than any of the component CIs. Similarly, the CI of a parallel system should be higher than any of the component CIs, which invalidates equations 3.1 and 3.2.

For example, using the structure in Fig. 4.4 and the probabilities of failure in Fig. 4.10, the approaches are compared at Year 0 and Year 40 of structural life. Table 4.1 shows the probabilities of failure for the components at Year 0 and Year 40, as well as the CI for sub-system A and the overall system using the currently proposed approach. Subsystem A is a parallel system consisting of components A1, A2, and A3, which are all behaving the same. If the components are independent, the reliability of subsystem A at Year 0 is determined using Eq. 2.12:

$$CI_{Sub-sys-A} = (0.0000274)(0.0000274)(0.0000274) = 2.07*10^{-14} \tag{4.25}$$

If the components are perfectly correlated, then the reliability is equal to the reliability of the strongest component

$$CI_{Sub-sys-A} = p_{f,\min} = 0.0000274 \tag{4.26}$$

Similarly, if the system components (Subsystem A, Components B and C) are independent, the reliability of the overall system at Year 0 is determined by Eq. 2.10 for the series system as:

$$CI_{system} = 1-[(1-2.07*10^{-14})(1-2.01*10^{-7})(1-0.0000274)] = 0.0000277 \tag{4.27}$$

If the components are perfectly correlated, then the reliability is equal to the reliability of the weakest component

$$CI_{system} = p_{f,\max} = 0.0000274 \tag{4.28}$$

Table 4.1 shows these results for both Year 40 and Year 0. There is a large difference between the results obtained using the currently proposed method and the traditional reliability approach, even on this small hypothetical structure, because the two approaches are measuring different things. Since most structures are series systems, the traditional reliability approach, whether one is looking at statistical independence or perfect correlation, reflects the probability of any small thing, however minor, going wrong on the system. On the automobile example, it might mean a dead battery, a burnt out headlight, or a hole in the muffler. As parts of a series system, any of those would cause the system to fail and some action would need to be taken before the automobile could be safely operated again. There is no way to account for the importance of components, so a faulty tail light is viewed with the same degree of seriousness as a blown engine in the evaluation of the system. In this simple example, there was not a big difference between the results when considering independence versus perfect correlation. For a seven level hierarchy, the difference will be more pronounced and considering correlation between components becomes more important.

The proposed CI method measures the likelihood of replacing or overhauling the entire system. It allows two similar systems with different distresses to be compared in terms of allocation of scarce maintenance dollars. The importance of components is fully considered in the analysis. A tail light would have such minor importance that the system CI would be negligibly affected by it. This makes sense as nobody would replace or rehabilitate an automobile based on a faulty tail light, but they would over a blown engine.

The two approaches are different in what they are attempting to measure and would almost never produce the same answer. In a series system, the probability of failure will always be at least as high as that of its weakest member. The probability of failure in a parallel system will always be as low as or lower than that of its strongest member. Using the weighted-average approach advocated here, the probability of failure of the system will always be somewhere between that of its strongest and weakest member.

3. A third approach is to recognize that any CI value above component level is meaningless and should not be used because it is misleading. Foltz *et.al.* (2001) acknowledge that there is considerable disagreement on the need for system or summary condition indices. Those most opposed are those who favor using CI data for reliability assessment and would advocate the traditional reliability approach over the system behavior proposed here. A system CI, if well constructed, provides valuable summary information in a standardized context on the condition of an entire class of structures. Such information is a highly credible means of describing the state of the infrastructure for funding priorities and public safety. It is also the only way to compare which structures most need to be replaced or rehabilitated.

4.10 Summary

This chapter has developed a methodology for using CI ratings based on visual inspection results to perform a type of risk based analysis of a structure. The approach was illustrated on a hypothetical series-parallel structure. Through a series of assumptions, failure and condition state randomness were defined, component and system CIs were computed, and a cost-benefit analysis involving the reliability index, probability of failure and hazard function was performed. The example problem demonstrated how these assumptions can be updated and modified over time as actual inspection data become available. The issues associated with system level CIs were discussed.

The example illustrates another danger of using higher level CI ratings for structures. It is easy to neglect a minor component that must be repaired or replaced for the structure to function. If a failing component has a small importance factor and other components are performing better than expected, it could easily be missed by an analyst looking only at structure-level CIs. Returning to the analogy of the automobile, while nobody would justify a major rehabilitation or replacement of an automobile because the battery is dead, the car will still not function without a new battery. The system needs a safeguard, such as a red flag whenever any component CI mean value rating falls below $CI=40$ and a conscious decision to repair or not repair needs to be made. With the methodology demonstrated on a small hypothetical structure, the next chapter will attempt to apply it the complex and very real Great Falls spillway structure used by Chouinard *et.al.* (2003).

Table 4.1: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components

Year 0				
Item	Probability of Failure			
	Component	System: Current Approach	System: Traditional Approach Statistical Independence	System: Traditional Approach Perfect Correlation
Component A	2.75E-05			
Component B	2.00E-07			
Component C	2.75E-05			
Sub-system A		2.75E-05	2.07E-14	2.75E-05
Struct. System		4.59E-07	2.77E-05	2.75E-05
Year 40				
Item	Probability of Failure			
	Component	System: Current Approach	System: Traditional Approach Statistical Independence	System: Traditional Approach Perfect Correlation
Component A	0.1984			
Component B	0.0583			
Component C	0.3665			
Sub-system A		0.1984	0.0078	0.1984
Struct. System		0.1076	0.4081	0.3665

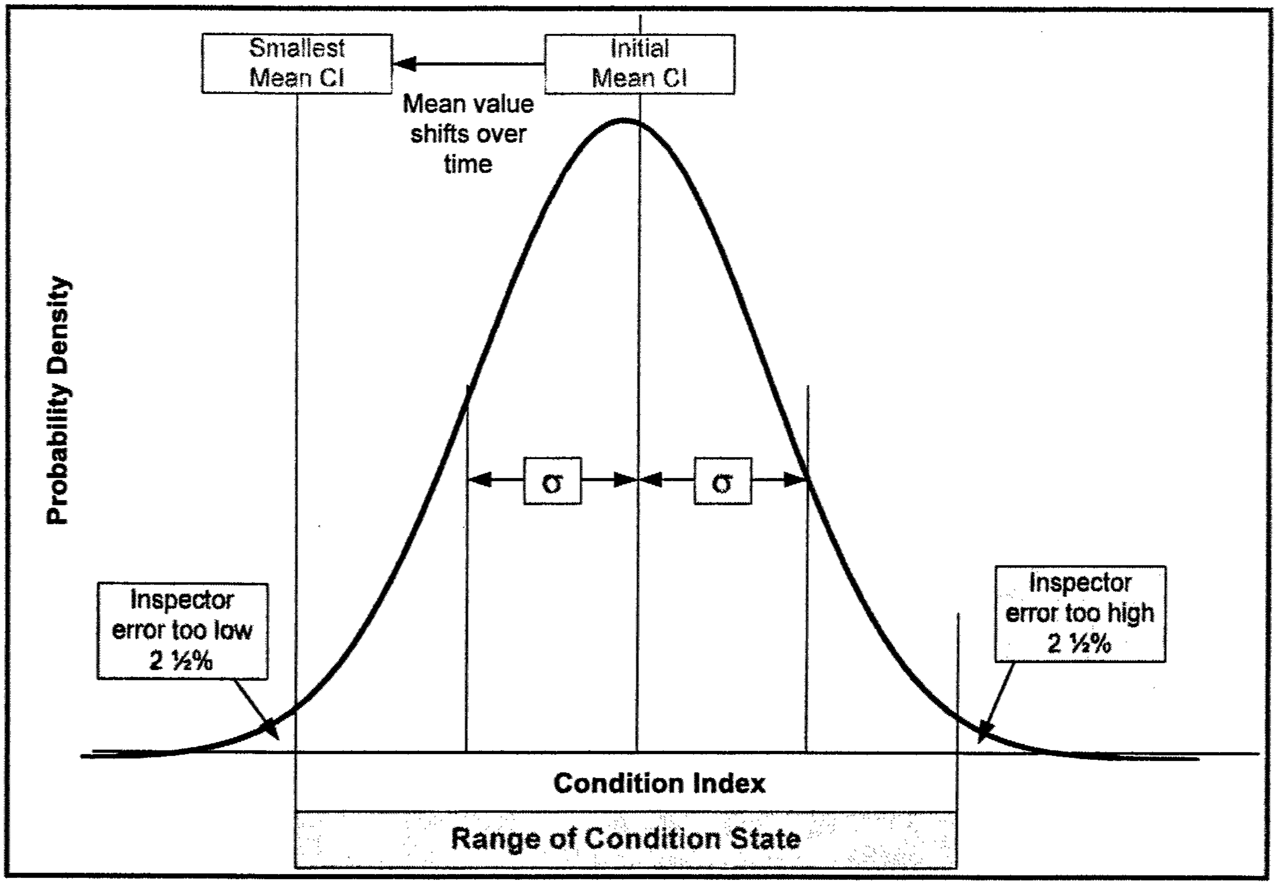

Figure 4.1: Typical Condition State Definition in Probabilistic Terms

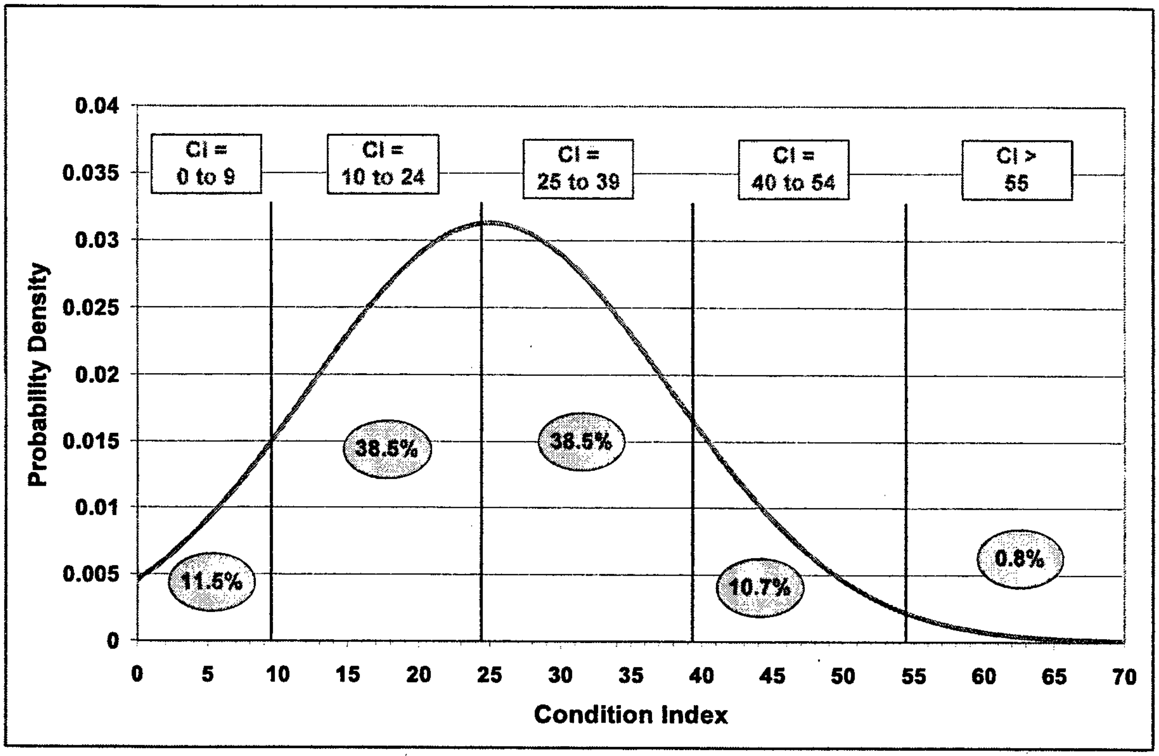

Figure 4.2: CI Definition of Failure in Probabilistic Terms

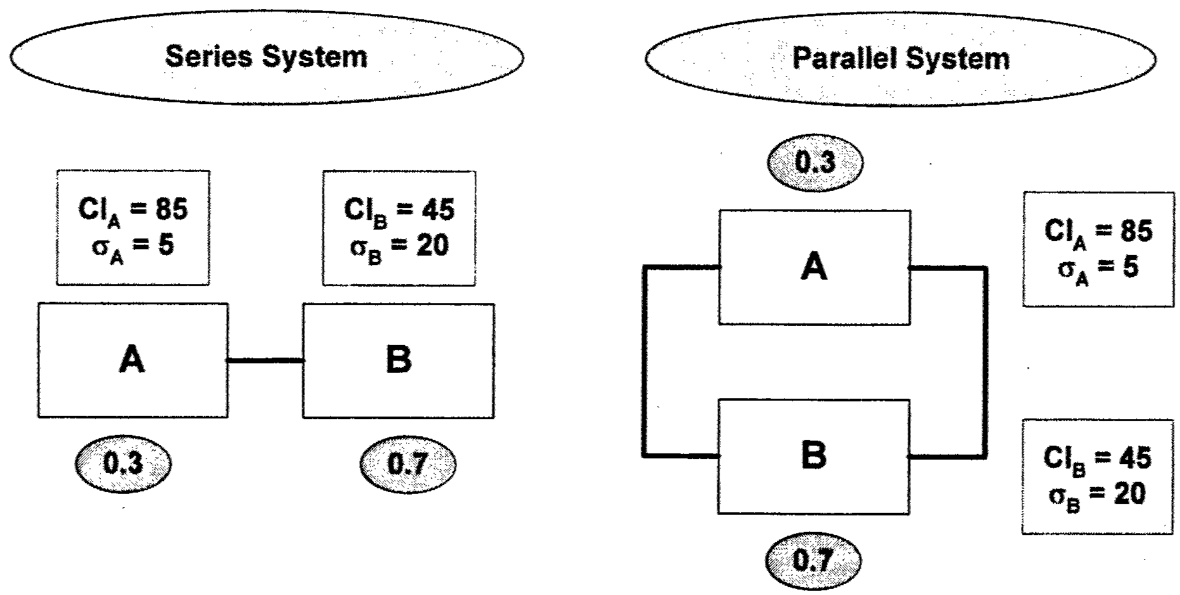

Figure 4.3: Simple Series and Parallel Systems Consisting of Components A and B

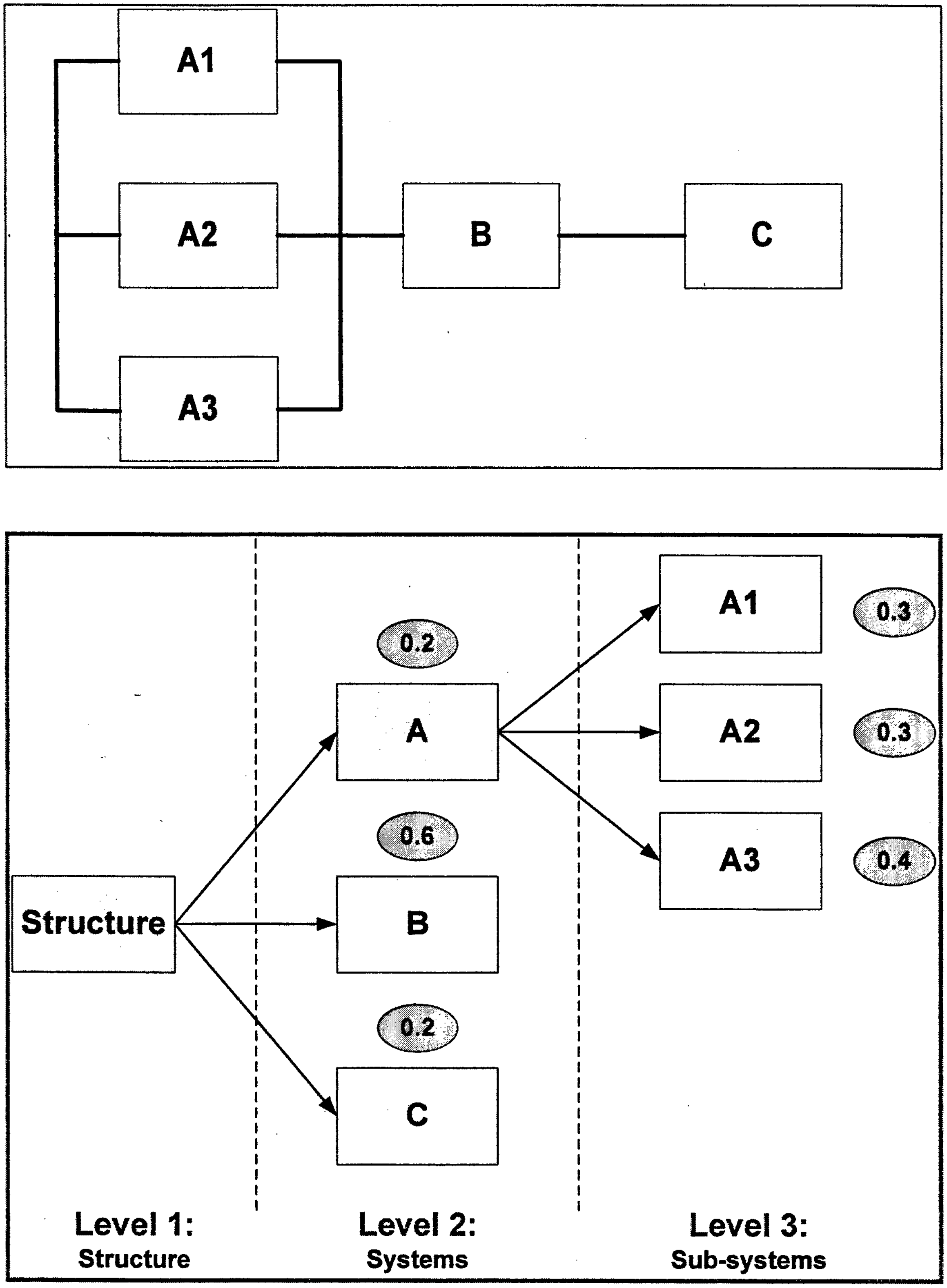

Figure 4.4: (a) Hypothetical Series-Parallel Structure, (b) Structural Hierarchy for Hypothetical Structure

Component A									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1						x	x	85	7.65
2			x	x	x			47	11.22
3		x						17	3.57
4	x							4.5	2.29

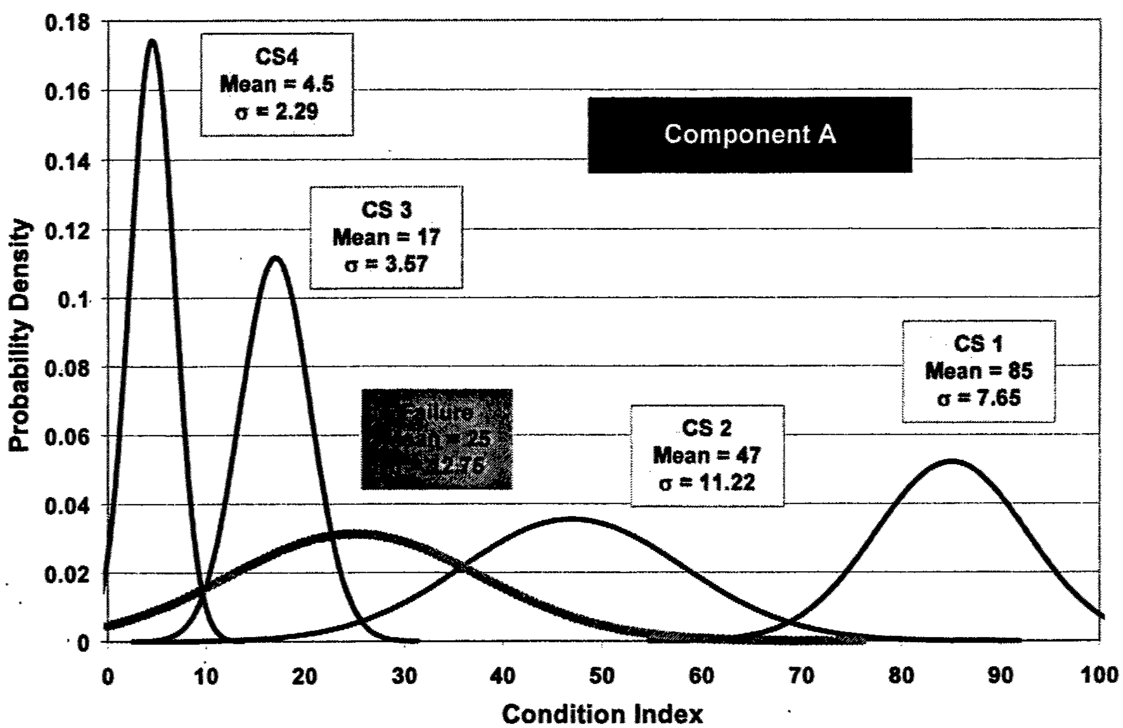

Figure 4.5: Condition Table and Distribution for Component A which is Applicable for Components A1, A2, and A3

Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1							x	92.5	3.82
2						x		77	3.57
3					x			62	3.57
4				x				47	3.57
5			x					32	3.57
6		x						17	3.57
7	x							4.5	2.29

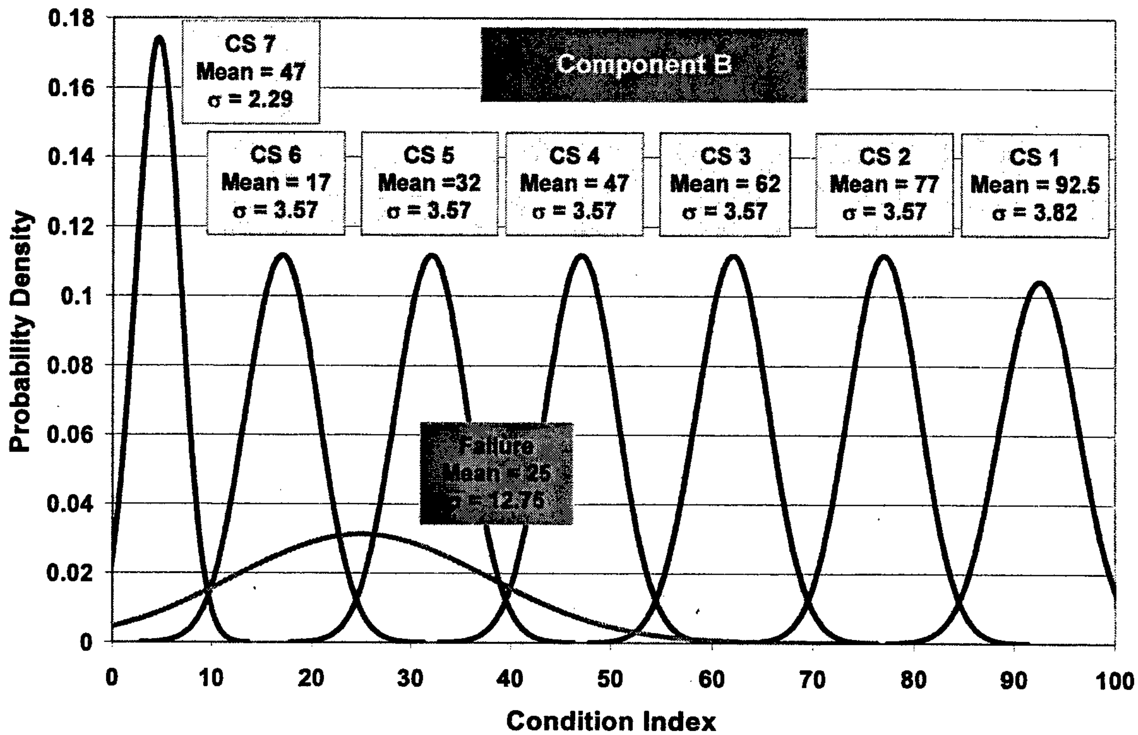

Figure 4.6: Condition Table and Distribution for Component B

Component C									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1						x	x	85	7.65
2		x	x	x				32	11.22
3	x							4.5	2.29

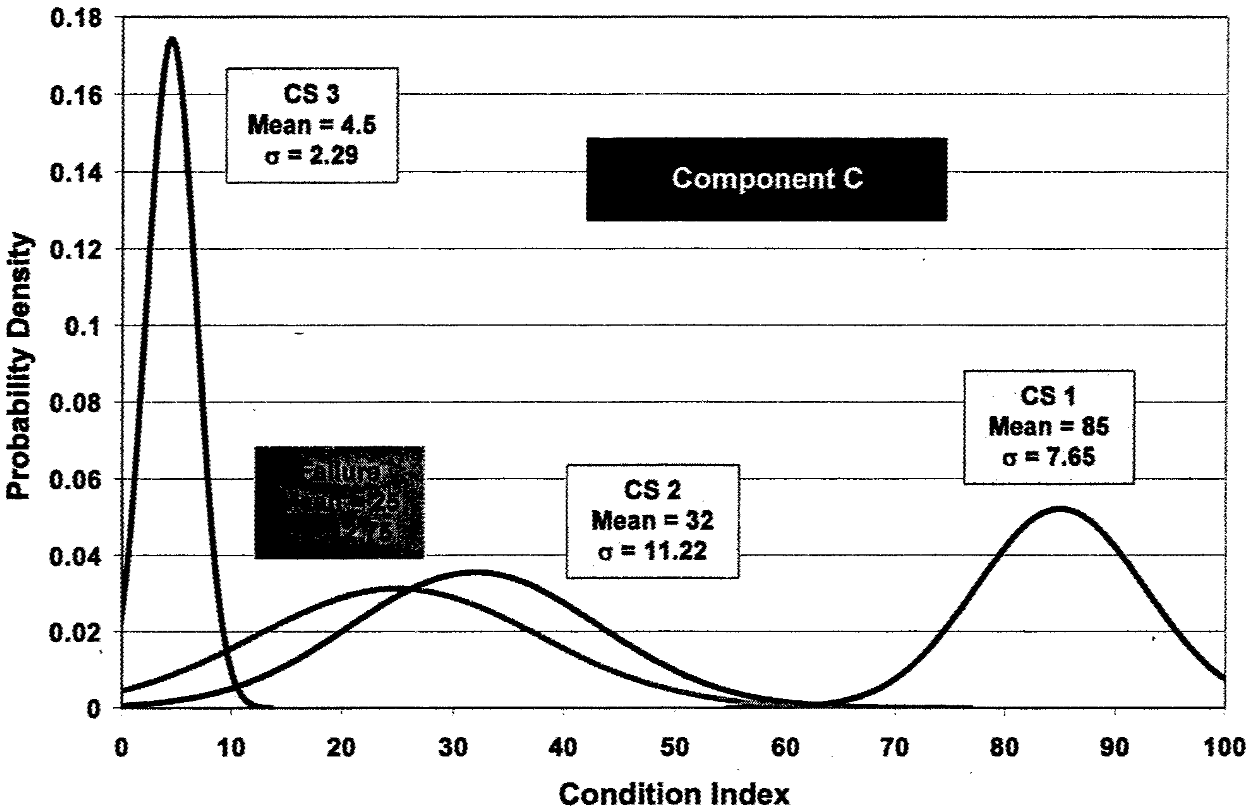

Figure 4.7: Condition Table and Distribution for Component C

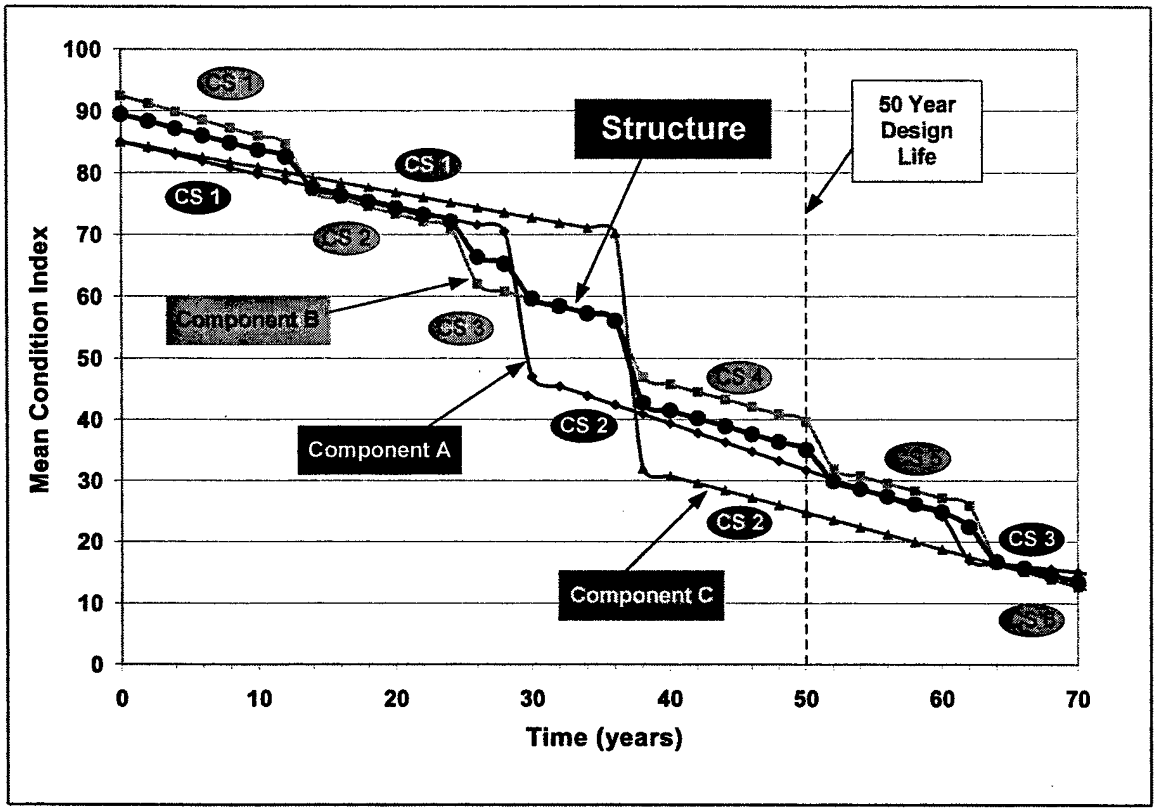

Figure 4.8: Expected Condition State Transition for the 50 Year Life of Components A, B, and C and the Entire Structure. Data Points are the Mean CI Values at Points in Time.

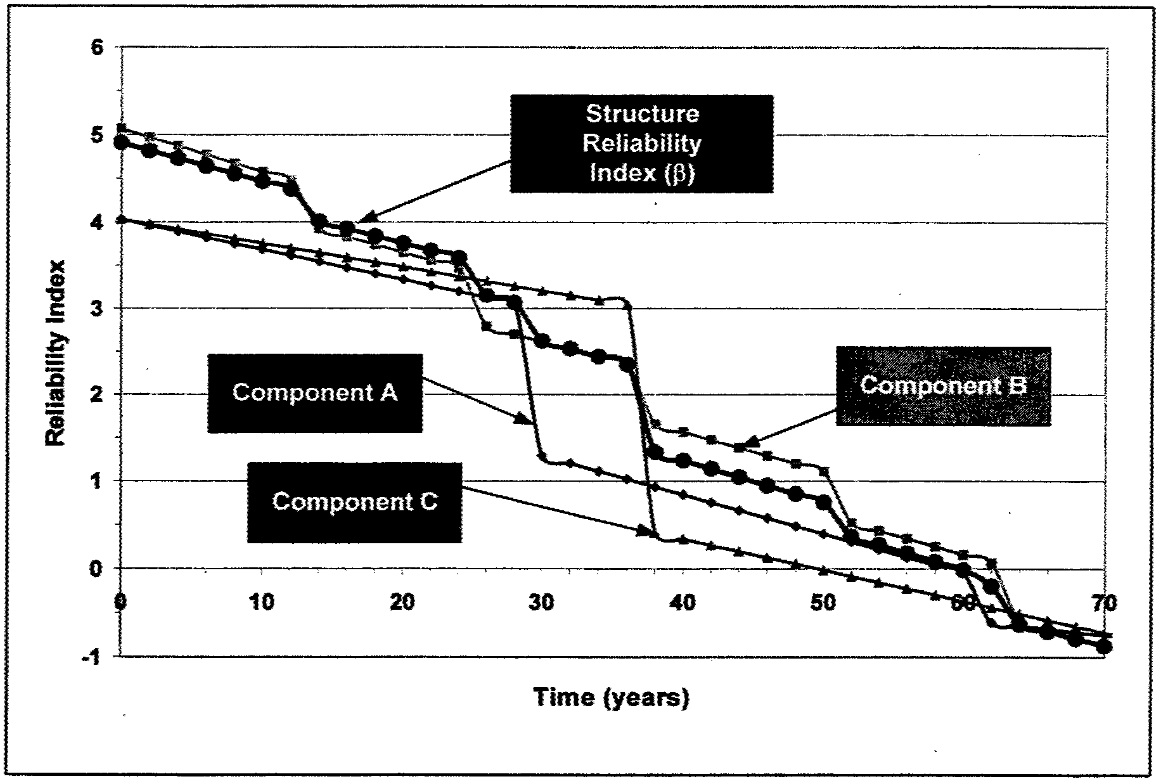

Figure 4.9: The Reliability Index (β) for Components A, B, and C and the Entire Structure over a 70 Year period.

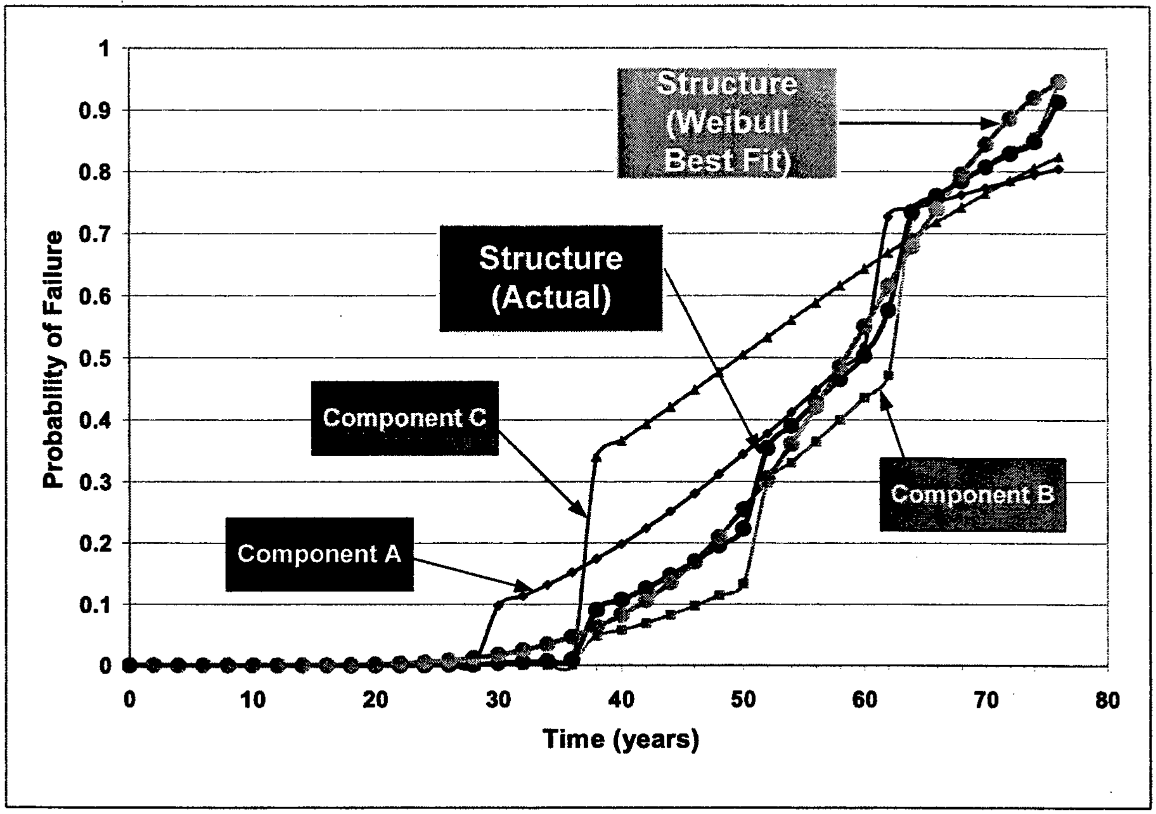

Figure 4.10: The Probability of Failure for Components A, B, and C and the Entire Structure over a 70 Year period.

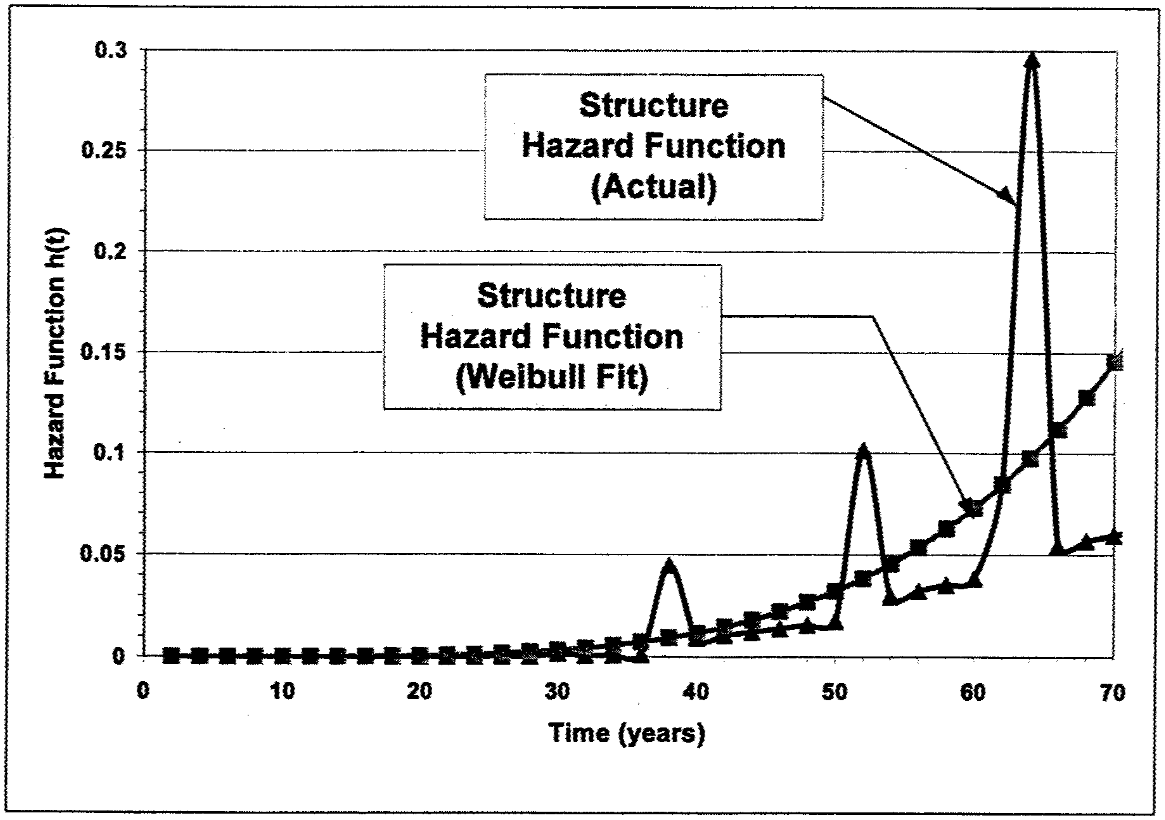

Figure 4.11: Hazard Functions for a Structure Based on Actual Results and the Best Fit Weibull Distribution Through the Data

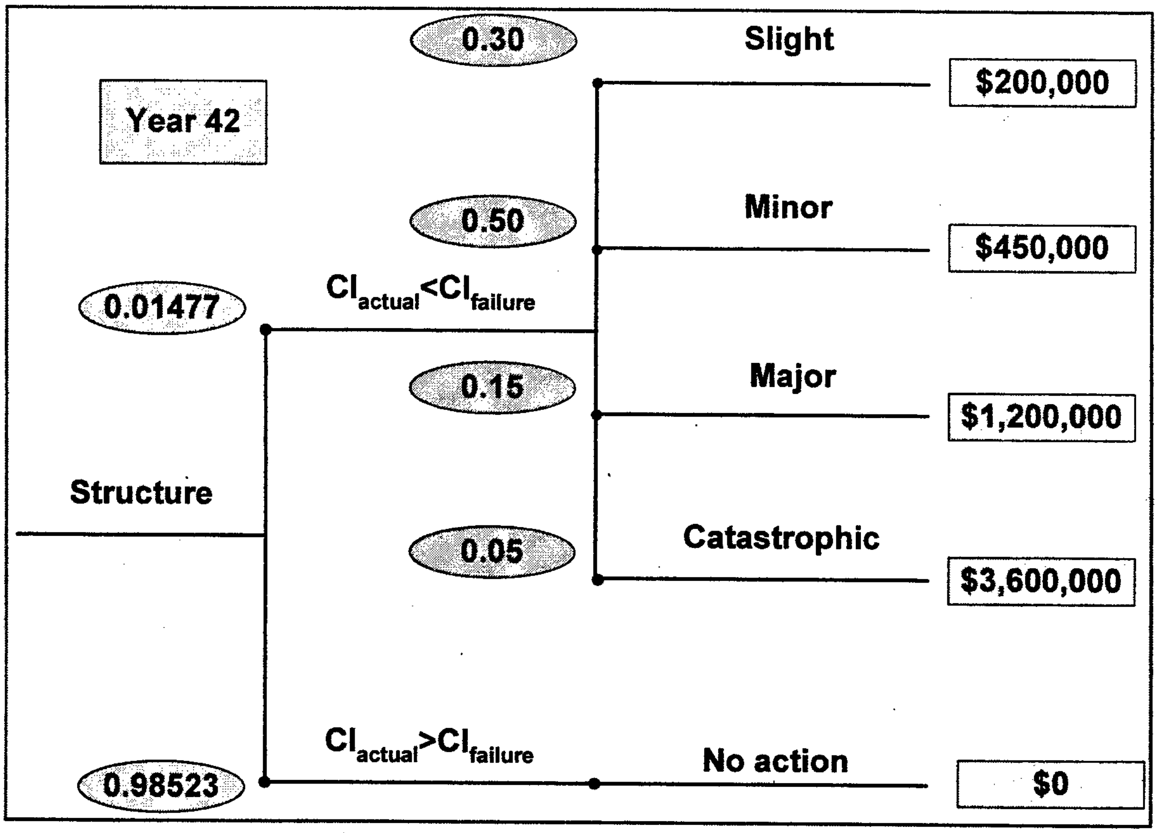

Figure 4.12: Cost Failure Tree for Structure at Year 42 of Useful Life Based on Consequences of Failure and Hazard Function

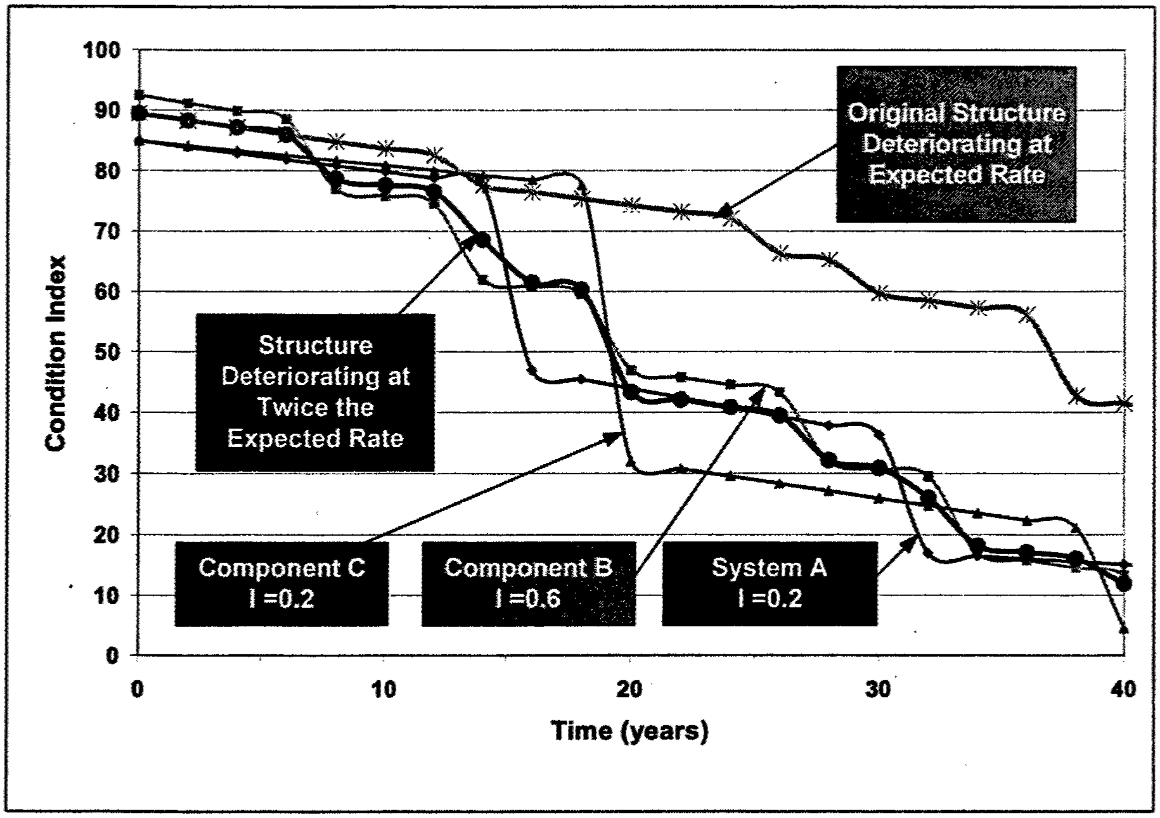

Figure 4.13 Mean Condition Index for a Structure that is Deteriorating at Double the Predicted Rate.

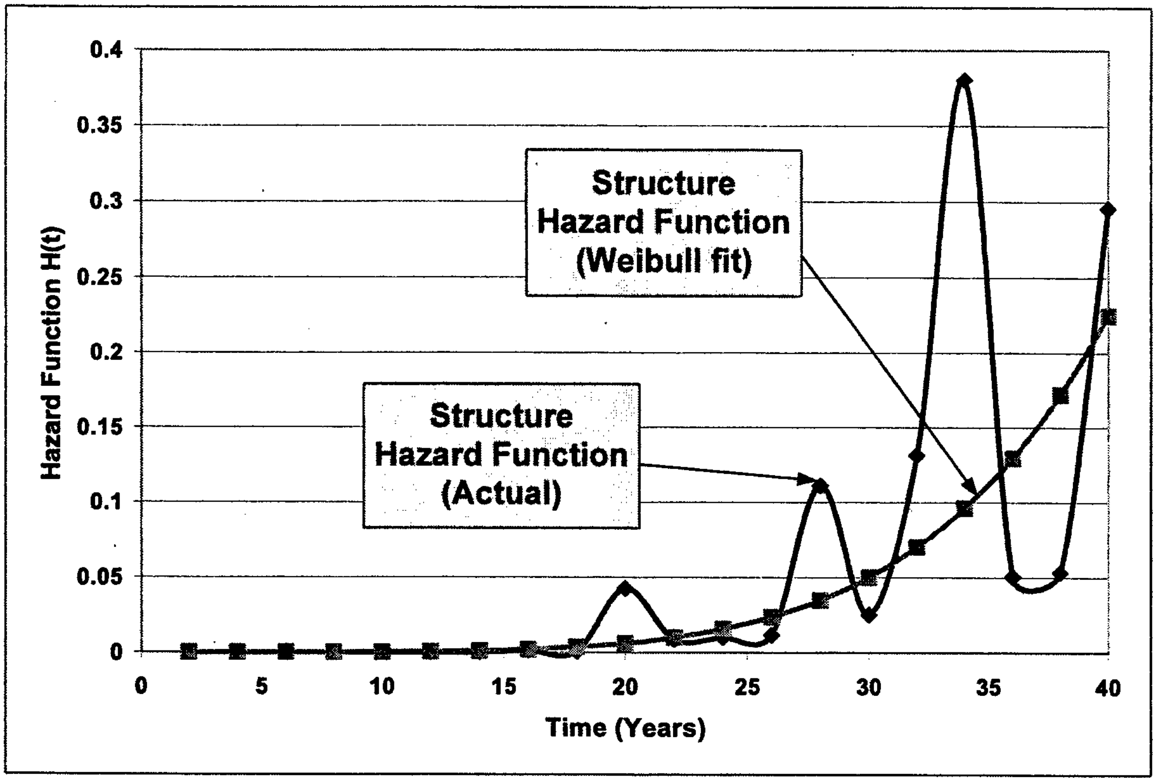

Figure 4.14: Hazard Functions Based on Actual Results and the Best Fit Weibull Distribution Through the Data for a Structure that is Deteriorating at Twice the Expected Rate.

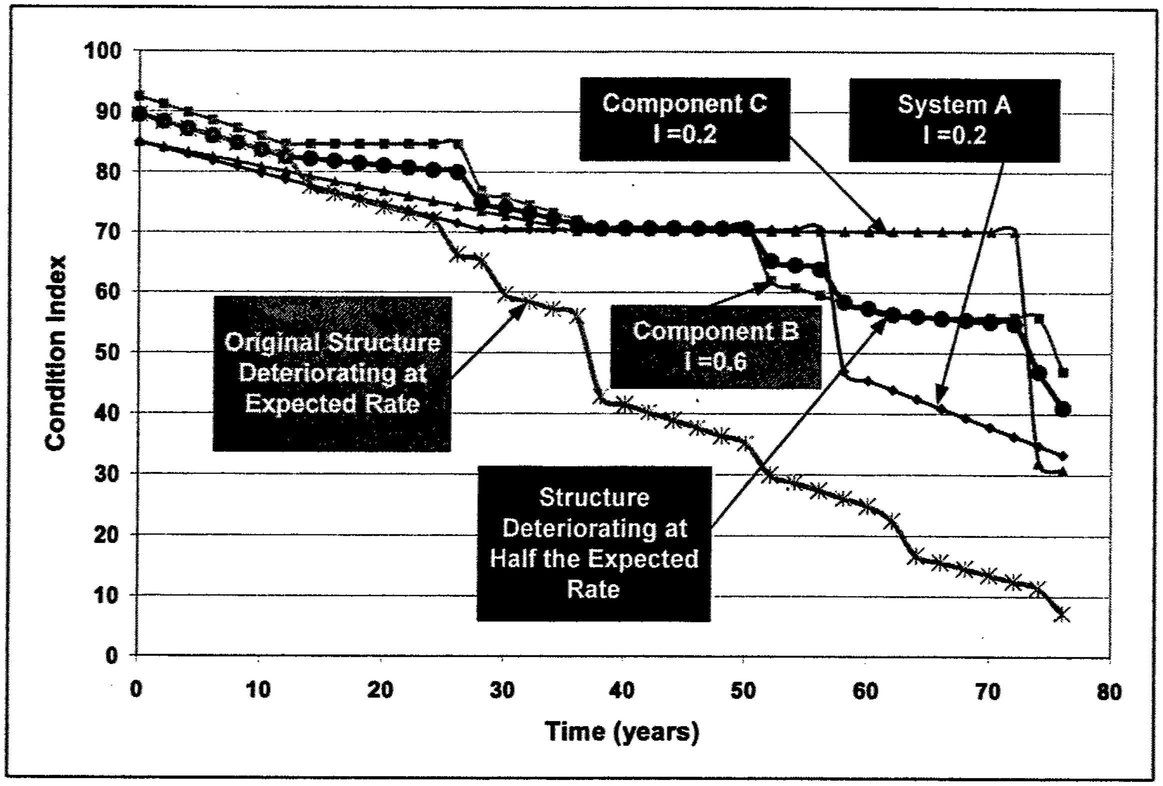

Figure 4.15 Mean Condition Index for a Structure that is Deteriorating at Half the Predicted Rate.

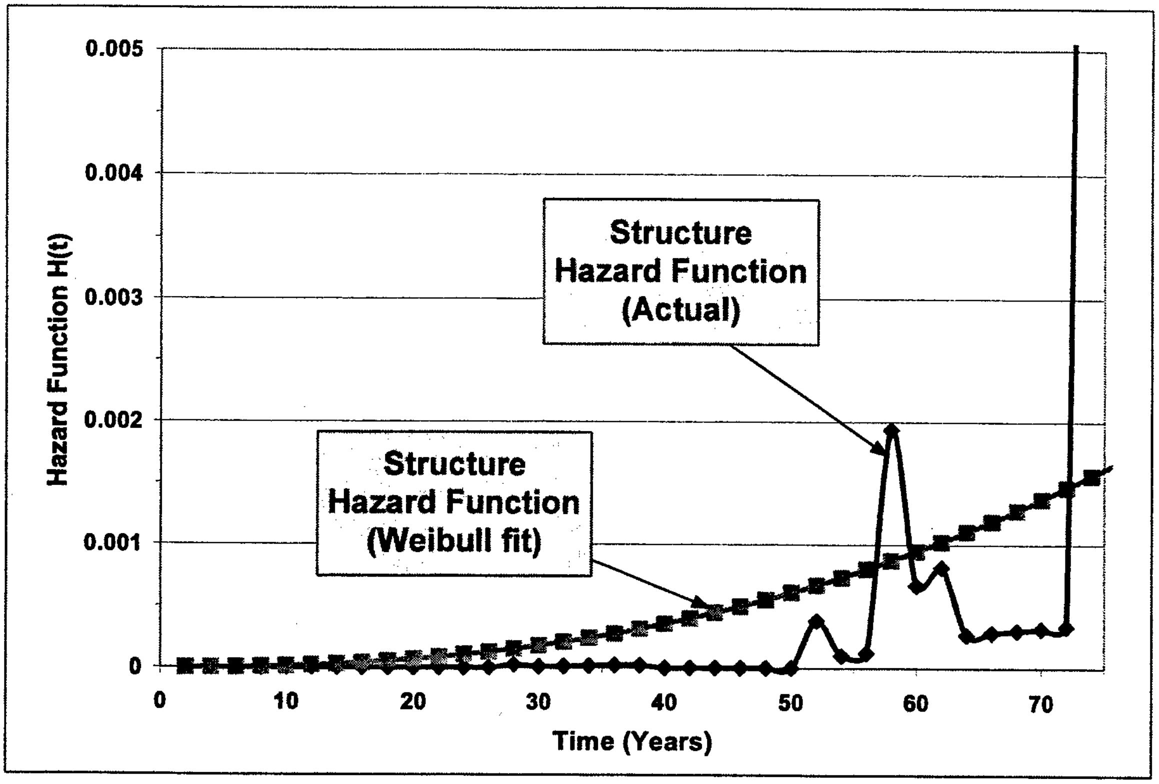

Figure 4.16: Hazard Functions Based on Actual Results and the Best Fit Weibull Distribution Through the Data for a Structure that is Deteriorating at Half the Expected Rate.

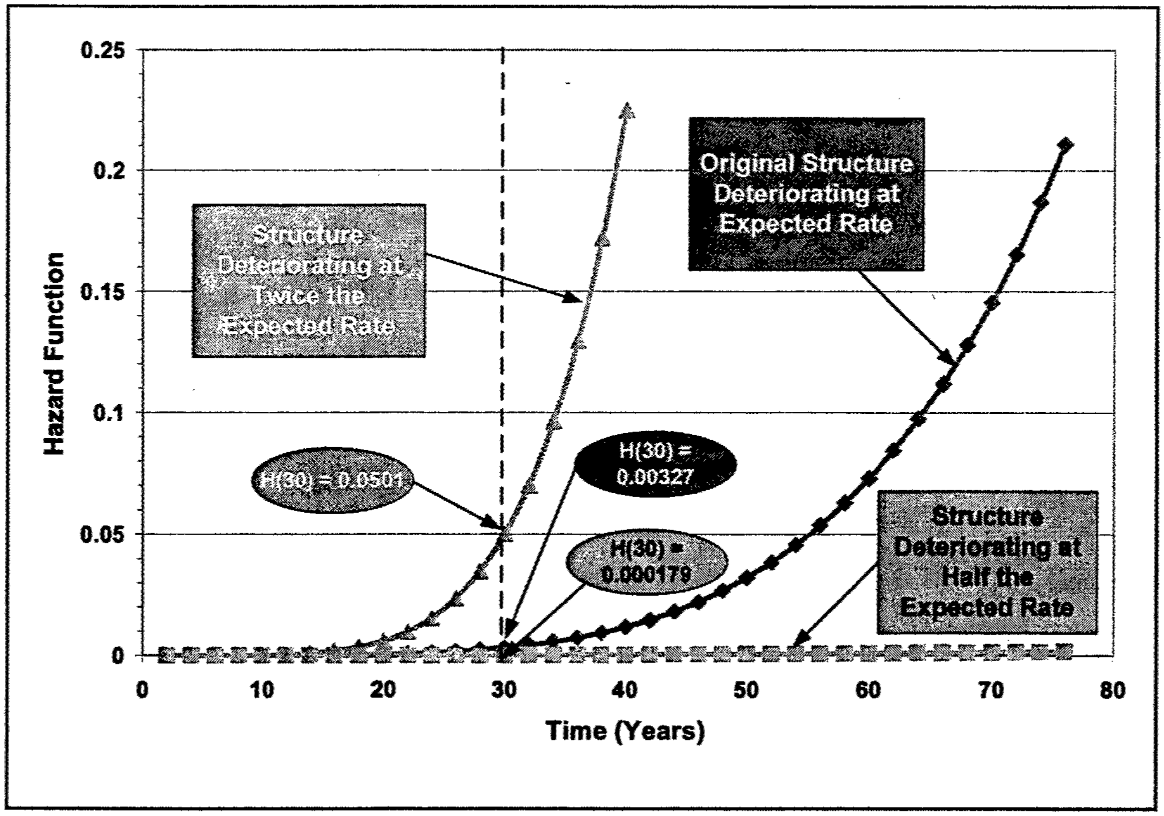

Figure 4.17: Hazard Functions for Structures that are Deteriorating at the Expected Rate, Twice the Expected Rate, and Double the Expected Rate.

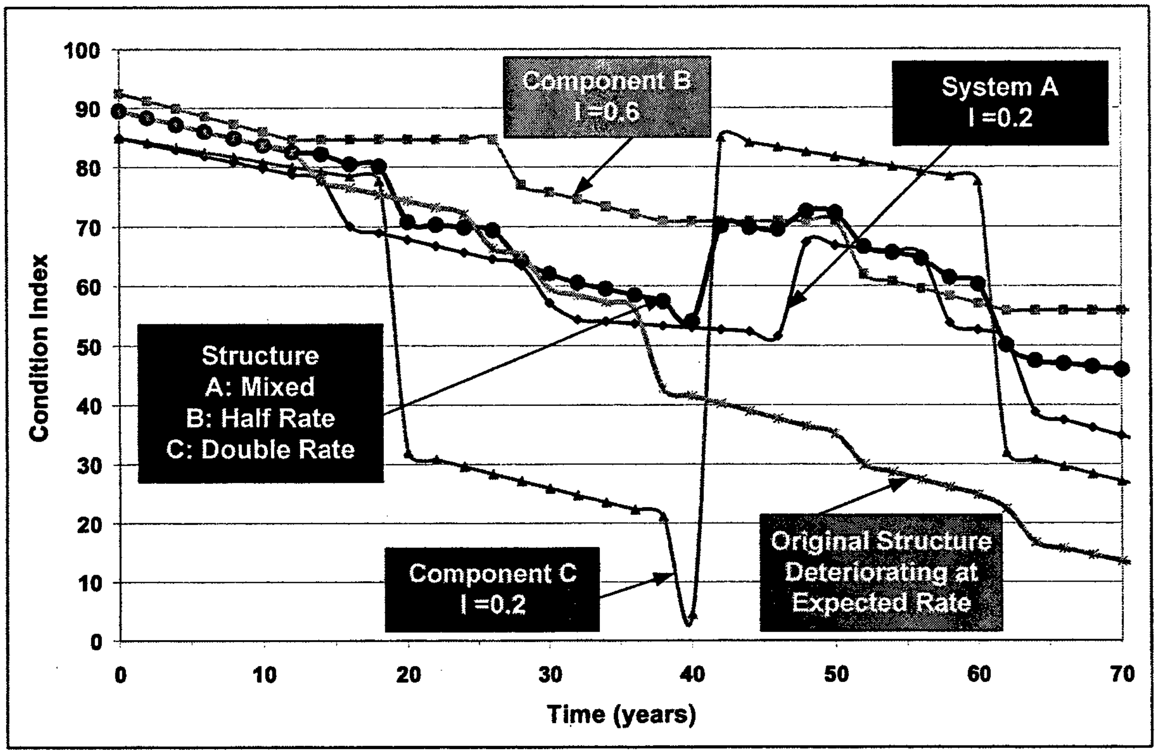

Figure 4.18: Mean Condition Index for a Structure Where Components A1 and B are Deteriorating at Half the Predicted Rate and Components A3 and C are Deteriorating at Double the Predicted Rate.

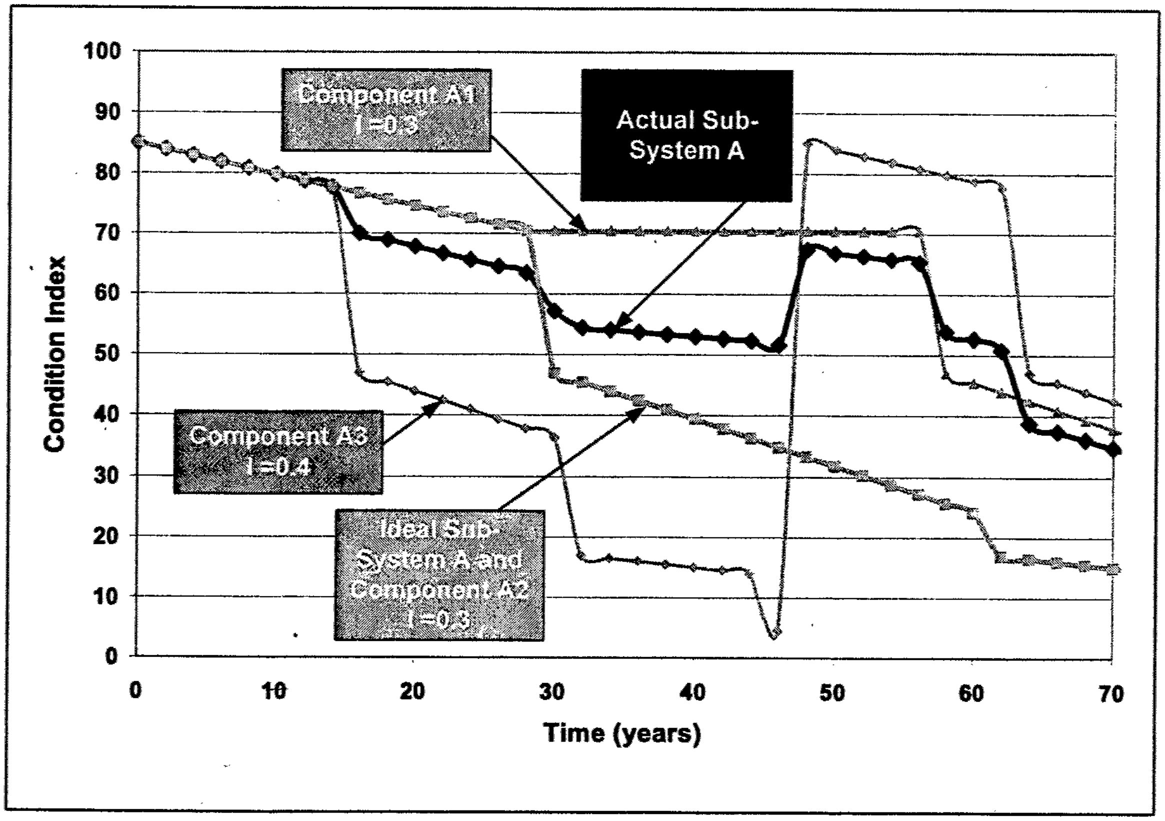

Figure 4.19: Mean Condition Index for Parallel System A Where Component A1 is Deteriorating at Half the Predicted Rate and Component A3 is Deteriorating at Double the Predicted Rate and A2 is Deteriorating at the Expected Rate.

Chapter 5: The Great Falls Spillway

5.1 The Structural Hierarchy

The Great Falls Dam shown in Fig. 5.1 is one of six dams and power plants managed by Manitoba Hydro on the Winnipeg River. The power plant has a 132 MW capacity, and the spillway is capable of discharging 4,390 cubic meters per second of water. Construction was completed in 1928 (Manitoba Hydro 2004). The Great Falls Spillway consists of four 80 meter long vertical lift gates with each having its own dedicated hoist (Chouinard *et.al.* 2003). The dam hierarchy is shown in Fig. 5.2 and consists of seven levels. The highest level (Level 1) is not shown and reflects the overall spillway structure. Higher levels are possible if one considers the entire dam and power plant structure where the spillway is one element of that structure. An even higher level is possible if the entire system of dams along the Winnipeg River is analyzed and the Great Falls dam is one structure in the Pine Falls, Great Falls, McArthur Falls, Seven Sisters, Slave Falls, Pointe Du Bois system.

Level 2 represents the dam safety functions, which are the various failure modes. They include overtopping due to a design flood, overtopping due to a load rejection, an unintentional opening, failure to close, and drawdown of reservoir to prevent a dam failure. This report examines overtopping due to a design flood as shown in Fig. 5.2. Chouinard *et.al.* (2003) considers all five failure modes. The procedure is essentially the same for all failure modes with only the importance factors changing. Since there is only one type of gate, level 3 is bypassed directly to level 4 which divides the spillway system into operational systems and equipment systems. The operations systems shown in level

5 consist of the information needed to make a decision, the decision process itself, and the ability to get people to the equipment they need to operate. The equipment systems represent the hoist/gate system and the electrical system that provides the power. These systems are divided into the sub-systems in level 6. The hoist/gate sub-system consists of the spillway gates, their lifting mechanisms and the support structure. Because each gate has its own dedicated hoist, the hoist/gate sub-system is modeled as a parallel-series system shown in Fig. 5.3.

Each of these sub-systems is further broken down into components and sub-components indicated by the letters *a* through *h* in Fig. 5.2. Figs. 5.4 through 5.9 show the components that these letters represent. Fig. 5.4, for example, shows the components and sub-components for the Gathering Information system. The information components include snow measuring stations, a flow prediction model, water level indicator system, gate position indicators, etc. Those blocks indicated by light blue (light) are inspected directly and classified according to the categories listed on a component table. The table number (i.e., C.2, C.4) from Chouinard *et.al.* (2003) is listed in the figures. The component table for snow measuring stations, for example, is shown in Table 5.1. There are three condition states and they are subjective, rather than objective in their description. The second condition state has a substantial range from $CI = 25$ to $CI = 69$. There are some ranges (10-24 and 70-84) that are not represented. This is acceptable as further definition and delineation may not be possible. Generally, a better and more credible assessment of structural condition will be obtained if the component can be divided into as many clearly defined condition states as possible.

Those components in yellow (dark) were not inspected directly. Their CI scores were obtained from sub-component CI results and importance factors. Table 5.2 shows the component table for the Reservoir Level Indicator System. It consists of three sub-components: water level indicators, data acquisition device, and data transmission. These sub-components are classified into six, four and four condition states, respectively. These condition states have differing ranges of CI values that will produce differing degrees of uncertainty in their results. Fig. 5.5 follows the same convention for the components and sub-components that comprise the Decision Process and the Access and Operations systems. Fig. 5.6 covers the Power Supply, Cables and Controls, and Support Structure systems. Fig. 5.7 is the gate system and Figs. 5.8 and 5.9 look at the hoist system components and sub-components.

Chouinard *et.al.* (2003) appeared to use the lowest score of sub-components and components to derive CI scores for sub-systems and systems. This study opted to use importance factors at all levels. This maintains a pure hierarchy and allows a component with multiple deficiencies to be distinguished from a component with only one. If a red flag is implemented whenever $CI < 40$ at the lowest inspectable level, there should be no danger of a deficiency going unnoticed. The importance factors are listed in Figs. 5.2 through 5.9. Those listed in purple (dark) circles were obtained from expert opinion and used in Chouinard *et.al.* (2003). Those shown in light green (light) were developed for this report, with the assumption of equal importance among sub-components, unless there was a compelling reason to assume something else.

5.2 Inspection Results

The actual inspection results from the Great Falls Spillway were used to apply the methodology proposed herein to this structure. Using the hierarchy shown in Figs. 5.2 through 5.9, the inspection results were combined with the importance factors shown in these figures to obtain the mean CI values, standard deviations, reliability indices, and probabilities of failure for the components and systems at each level. The starting point was the inspection results. It is assumed throughout that this is an initial inspection and the mean value will be at the midpoint of the condition state. If these were follow-on inspections, the mean value would shift as described in Section 4.5 and Fig. 4.1. The mean value and standard deviation for the Reservoir Level Indicator System is obtained from the inspection results in Table 5.2 using equation 4.2.

Water Level Indicator: Range Classified by Inspector --- 85-100

Mean Value: CI = 92.5

Standard Deviation: $$\sigma = \frac{100-92.5}{1.96} = 3.83 \tag{5.1}$$

Data Acquisition Device: Range Classified by Inspector --- 40-84

Mean Value: CI = 62.0

Standard Deviation: $$\sigma = \frac{84.0-62.0}{1.96} = 11.22 \tag{5.2}$$

The computations for the Data Transmission sub-component are the same as the Water Level Indicator. In the actual inspection, the inspector was given considerable leeway in producing an actual CI score. The inspector chose to give the Water Level Indicator a CI score of 85, the lowest in the category, but gave the Data Transmission a CI score of 95. The inspector gave the Data Acquisition Device a CI score of 65, which is somewhere in the middle of a fairly large condition state. There is no guarantee that another inspector would see it the same way. The approach proposed in this study only asks the inspector to choose the correct condition state, which should provide much greater consistency between inspectors and thus, CI scores.

The mean CI and standard deviation for the Reservoir Level Indicator Component which is a series system comprised of the Water Level Indicator, Data Acquisition, and Data Transmission subcomponents are computed using equations 4.3 and 4.4.

$$CI_{RLI-Component} = \sum_{j=1}^{n} I_j CI_j = (0.33)(92.5) + (0.33)(62.0) + (0.33)(92.5) = 82.3 \tag{5.3}$$

$$\sigma_{CI_{RLI-Component}} = \sqrt{\sum_{j=1}^{n} I_j^2 \sigma_j^2} = \sqrt{(0.33)^2(3.83)^2 + (0.33)^2(11.22)^2 + (0.33)^2(3.83)^2} = 4.15 \tag{5.4}$$

The reliability indices and probabilities of failure are computed using equations 2.4 and 2.5

$$\beta_{RLI-Component} = \frac{82.3 - 25}{\sqrt{(4.15)^2 + (12.5)^2}} = 4.27 \tag{5.5}$$

$$p_{f,RLI-Component} = \Phi(-4.27) = 9.61(10)^{-6} \tag{5.6}$$

Using the same approach for the other components and sub-components, Table 5.3 shows the results for the Gathering Information, Decision Process, and Access and Operations systems. The components and sub-components are numbered to reflect the hierarchy shown in Figs. 4.2 through 4.9. The importance factors, mean CI value, standard deviation, and reliability index are listed. Those rows in light blue (light) were inspected directly from the Component Table listed and those rows in yellow (dark) reflect higher order indices derived from a combination of inspection results and importance factors. Table 5.4 shows the same information for the components and sub-components of the Power Supply, Cables and Controls, and Supporting Structure sub-systems. Tables 5.5 and 5.6 reflect the Gate and Hoist sub-systems, respectively.

Table 5.7 combines the results from Tables 5.3 through 5.6 to provide the CI and reliability results for the sub-systems, systems, and overall structure. The mean CI of the overall structure is $CI=84.02$. The structure is in excellent condition and the reliability index of $\beta=4.61$ reflects little likelihood that it needs to be replaced or rehabilitated. The least functional system of the structure was the Decision Making Process. It was part of the Operational System which was given a smaller importance factor ($I=0.3$) than the Equipment System ($I=0.7$) and thus had less effect on the overall structure rating.

Assuming that the components were all independent caused the standard deviation of the condition indices to get progressively smaller as the calculations progressed up the hierarchy. This is not a conservative assumption as the smaller standard deviations will result in smaller reported probabilities of failure. An assumption of perfect correlation would have produce higher standard deviations at the system levels. Assuming either perfect correlation or estimating the actual correlation would have complicated the computations and would not necessarily have been any more correct. This issue merits further study.

Tables 5.3 through 5.7 illustrate that the methodology introduced in Chapter 4 on a simple hypothetical structure is equally applicable to a large complex structure and the level of difficulty is not much higher than a deterministic analysis. The condition of the structure at successively higher levels reflects the inspection results and the relative importance of the various components. The best results will be obtained when the component condition tables are delineated into as many clearly defined condition states as practicable.

5.3 System Probability Approaches

Returning to the discussion in Section 4.9, the CI system proposed in this report is compared to the traditional reliability approach. Table 5.8 compares the two approaches for the Gathering Information, Decision Process, and Access and Operations Systems. Using the Reservoir Level Indicator from Table 5.2 as an example, the results from Table 5.3 indicate the following for the sub-components:

$$\begin{array}{lll} \text{Water Level Indicator} & \beta=5.07 & p_f=\Phi(-\beta)=\Phi(-5.07)=2.00(10^{-7}) \\ \text{Data Acquisition Device} & \beta=2.18 & p_f=\Phi(-\beta)=\Phi(-2.18)=0.0147 \\ \text{Data Transmission} & \beta=5.07 & p_f=\Phi(-\beta)=\Phi(-5.07)=2.00(10^{-7}) \end{array} \tag{5.7}$$

Eq. 5.6 computed the probability of failure using the current proposal. Assuming the components are independent, Eq. 2.10 is used to compute the probability of failure for the Reservoir Level Component which is a series system of the listed sub-components:

$$p_{f,RLI-Component} = 1-((1-2.00*10^{-7})(1-0.0147)(1-2.00*10^{-7})) = 0.0147 \tag{5.8}$$

Assuming the components are perfectly correlated, the component probability is:

$$p_{f,RLI-Component} = p_{f,\max-Sub-component} = 0.0147 \tag{5.9}$$

In this case, the independent and perfectly correlated results were identical because the probability of failure of the Data Acquisition Device was so much higher than that of the other two sub-components. The same process is used for the other components in Table 5.8. There was a larger discrepancy between the independent and perfectly correlated results for the Gathering Information system of which the Reservoir Level Indicator was a part -- 0.287 for independent versus 0.098 for perfectly correlated. Tables 5.9 through 5.11 show the same calculations for additional components, the gate and the hoist, respectively.

Table 5.12 shows the results for the higher level sub-systems, systems, and the entire structure. Using the proposed approach, the probability of failure, which reflects the probability of the structure needing replacement or rehabilitation is

$$p_{f,Structure} = 1.96 * 10^{-6}$$

This is a low likelihood of replacement which makes sense given the excellent condition of the structure and its most important systems and components. Whether that number is accurate at all merits further study. Using the traditional reliability approach, if the components are independent, the probability of failure is 0.445 and if they are perfectly correlated, the failure probability is 0.098. Given all the components and systems on the structure, there is somewhere between a 10% and 45% chance that something will fail somewhere on the structure. It will most likely occur in the Operations rather than the Equipment portion of the structure and some estimation of correlation becomes important.

One could argue that a traditional reliability analysis should never include the Gathering Information and Decision Process systems in the analysis. They do not truly represent series systems. If the snow measuring devices or the public protection warning system fail, they do not really affect whether the spillway gate will go up when it is needed. The system condition index described in this report does not lend itself well to traditional system reliability methods. An advantage to the approach used herein is that the analyst can incorporate anything that he or she thinks is relevant to the structure into the analysis. Because the goal is to attain an overall score for the structure to allow comparison with other structures, any variable can be included, even if it is difficult to define. One additional variable may be vulnerability of the structure to attack, sabotage, or terrorism, which will be the subject of the next chapter.

Table 5.1: Component Condition Table and Actual Inspection Results for Snow Measuring Stations – Part of the Gathering Information System on the Great Falls Dam

Snow Measuring Stations (Chouinard *et.al.* 2003 Table C.4)									
Function									
Excellent	Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes.								
Failed	Not measuring snow depth cover in the watershed where applicable.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 – 69	70 – 84	85 – 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes							X		Winter precipitation tracked but not evaporation etc; remote sensing used to obtain snow water contents; limited Env't Canada measurement sites; Info used qualitatively only - not in models.
Inadequate number of snow measurement locations and/or insufficient frequency of readings			X	X	X			50	
Not measuring snow depth cover in the watershed where applicable	X								

Table 5.2: Component Condition Table and Actual Inspection Results for Reservoir Level Indicator – Part of the Gathering Information System on the Great Falls Dam

Water Level Indicator System for Reservoir level (Chouinard et.al. 2003 Table C.2)									
Function									
Excellent	Providing accurate data, redundancy and no evidence of malfunction (water level in the reservoir) for dam safety purposes. Instrument regularly checked and calibrated.								
Failed	Not providing accurate data, not functioning.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 – 69	70 – 84	85 – 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Water level indicators									
Measuring level accurately and continuously and adequate number for dam safety purposes							X	85	Forebay water level gauge in powerhouse.
Inadequate water level indicators to determine the influence of wind on pool level				X	X	X			
Poorly located (influenced by gate opening or difficult to read)			X	X	X				
Inadequate frequency of measurement			X	X					
No redundancy (only one gauge near the dam or spillway)		X	X	X					
Not providing accurate data, not functioning	X								
Data acquisition device									
Recording data continuously accurately and reliably.							X		Aging equipment; accuracy dependent on gauge maintenance; historically somewhat troublesome.
Recording data intermittently but still adequate				X	X	X		65	
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data continuously accurately and reliably.							X	95	Data delivered via SCADA network; new communications equipment has improved reliability, problems now rare.
Transmittinging data intermittently but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								

Table 5.3: Condition Index and Reliability Results for the Gathering Information, Decision Process, and Access and Operations Systems on the Great Falls Spillway

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Gathering Information	7a		76.72	2.01	4.01	
River Flow Measurement	7a.1	0.11	82.33	4.15	4.27	C.1
Water Level Indicator	7a.1.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.1.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.1.3	0.33	62.00	11.22	2.18	
Reservoir Level Indicator	7a.2	0.11	82.33	4.15	4.27	C.2
Water Level Indicator	7a.2.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.2.2	0.33	62.00	11.22	2.18	
Data Transmission	7a.2.3	0.33	92.50	3.83	5.07	
Precipitation & Temp. Gauge	7a.3	0.11	77.33	4.15	3.90	C.3
Precip & Temp Gauges	7a.3.1	0.33	47.00	11.22	1.29	
Data Acquisition Device	7a.3.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.3.3	0.33	92.50	3.83	5.07	
Snow Measuring Model	7a.4	0.11	47.00	11.22	1.29	C.4
Flow Predicition Model	7a.5	0.11	47.00	11.22	1.29	C.9
Weather Forecasting	7a.6	0.11	77.00	3.57	3.93	C.5
Ice and Debris Management	7a.7	0.11	92.50	2.21	5.21	C.6
Monitoring	7a.7.1	0.33	92.50	3.83	5.07	
Management	7a.7.2	0.33	92.50	3.83	5.07	
Control Equipment	7a.7.3	0.33	92.50	3.83	5.07	
Gate Position Indicator	7a.8	0.11	92.50	2.21	5.21	C.8
Position Indicator	7a.8.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.8.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.8.3	0.33	92.50	3.83	5.07	
Third-Party Flow Data	7a.9	0.11	92.50	3.83	5.07	C.7
Decision Process	7b		62.10	4.27	2.76	
Data Processing	7b.1	0.20	92.50	3.83	5.07	Ssheet
Analysis	7b.2	0.20	47.00	11.22	1.29	Ssheet
Decision Process	7b.3	0.20	47.00	11.22	1.29	C.10
Public Protection Warning System	7b.4	0.20	62.00	11.22	2.18	C.12
Operation Procedures	7b.5	0.20	62.00	7.94	2.46	C.15
Standard Operating Procedures	7b.5.1	0.50	62.00	11.22	2.18	
Autonomous Operating Proc.	7b.5.2	0.50	62.00	11.22	2.18	
Access and Operations	7c		92.50	1.43	5.26	
Avail. and Mobilization (Load Rejectio	7c.1	0.20	92.50	2.71	5.18	C.14
Availablity	7c.1.1	0.50	92.50	3.83	5.07	
Mobilization	7c.1.2	0.50	92.50	3.83	5.07	
Avail. and Mobilization (Load Rejectio	7c.2	0.20	92.50	2.71	5.18	C.13
Availablity	7c.2.1	0.50	92.50	3.83	5.07	
Mobilization	7c.2.2	0.50	92.50	3.83	5.07	
Qualification / Training of Operator	7c.3	0.20	92.50	3.83	5.07	C.18
Local Access	7c.4	0.20	92.50	2.71	5.18	C.22
Pedestrian Access	7c.4.1	0.50	92.50	3.83	5.07	
Keys and Locks	7c.4.2	0.50	92.50	3.83	5.07	
Lighting System	7c.5	0.20	92.50	3.83	5.07	C.29

Table 5.4: Condition Index and Reliability Results for the Power Supply, Cables and Controls, and Supporting Structure Sub-Systems on the Great Falls Spillway

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Power Supply			86.25	2.07	4.74	
Local or Emergency Generators	7d	1.00	86.25	2.07	4.74	C.25
Frequency and Voltage	7d.1	0.08	85.00	7.65	4.03	
Engine Temperature / Oil Pressur	7d.2	0.08	85.00	7.65	4.03	
Starting Sequence	7d.3	0.08	85.00	7.65	4.03	
Noise and Vibratiion	7d.4	0.08	85.00	7.65	4.03	
Functional Test	7d.5	0.08	92.50	3.83	5.07	
Fuel	7d.6	0.08	92.50	3.83	5.07	
Batteries	7d.7	0.08	85.00	7.65	4.03	
Battery Charger	7d.8	0.08	85.00	7.65	4.03	
Alternator	7d.9	0.08	85.00	7.65	4.03	
Lubrication	7d.10	0.08	85.00	7.65	4.03	
Cooling System	7d.11	0.08	85.00	7.65	4.03	
Intake and Exhaust System	7d.12	0.08	85.00	7.65	4.03	
Cables and Controls	7e		87.94	2.57	4.84	
Underground and Encased Cables	7e.1	0.25	85.00	5.41	4.33	C.24
Insulation	7e.1.1	0.50	85.00	7.65	4.03	
Terminators	7e.1.2	0.50	85.00	7.65	4.03	
Power Feeder Cables	7e.2	0.25	85.00	5.41	4.33	C.25
Insulation	7e.2.1	0.50	85.00	7.65	4.03	
Terminators	7e.2.2	0.50	85.00	7.65	4.03	
Transformer	7e.3	0.25	89.25	5.69	4.60	C.26
Dielectric	7e.3.1	0.00	N/A	N/A	N/A	
Insulation	7e.3.2	0.50	85.00	7.65	4.03	
Windings	7e.3.3	0.55	85.00	7.65	4.03	
Tank	7e.3.4	0.00	N/A	N/A	N/A	
Power Source Transfer System	7e.4	0.25	92.50	3.83	5.07	C.27
Test (Transfer Switch)	7e.4.1	0.00	N/A	N/A	N/A	
Test (Manual Transfer Device)	7e.4.2	1.00	92.50	3.83	5.07	
Supporting Structure	6e		92.50	2.07	5.22	
Lifting Device Structure (Steel)	7f.1	0.50	92.50	1.56	5.25	C.64
Displacement / Deterioration	7f.1.1	0.17	92.50	3.83	5.07	
Anchor Bolts	7f.1.2	0.17	92.50	3.83	5.07	
Cracks	7f.1.3	0.17	92.50	3.83	5.07	
Distortion	7f.1.4	0.17	92.50	3.83	5.07	
Corrosion	7f.1.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7f.1.6	0.17	92.50	3.83	5.07	
Lifting Device Structure (Concrete)	7f.2	0.50	92.50	3.83	5.07	C.61

Derived from a Combination of Inspected Items

Directly Measured by Inspection

Table 5.5: Condition Index and Reliability Results for the Gate Sub-System on the Great Falls Spillway

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Gate #1	7g		90.48	1.25	5.11	
Gate Structure and Support	7g.1	0.90	90.26	1.17	5.09	
Approach and Exit Channel	7g.1.1	0.17	92.50	1.71	5.25	C.63
Loss of Concrete Apron	7g.1.1.1	0.20	92.50	3.83	5.07	
Loss of Concrete Pier/Base	7g.1.1.2	0.20	92.50	3.83	5.07	
Scour of Foundation	7g.1.1.3	0.20	92.50	3.83	5.07	
Upstream Sedimentation	7g.1.1.4	0.20	92.50	3.83	5.07	
Downstream Blockage	7g.1.1.5	0.20	92.50	3.83	5.07	
Embedded Parts	7g.1.2	0.17	80.30	3.28	4.20	C.65
Gate Lifting Effort	7g.1.2.1	0.20	92.50	3.83	5.07	
Geometrical Alignment Roller	7g.1.2.2	0.20	62.00	11.22	2.18	
Roller Path Corrosion	7g.1.2.3	0.20	69.50	7.40	3.02	
Roller Tooth Wear	7g.1.2.4	0.20	92.50	3.83	5.07	
Corrosion Remainder	7g.1.2.5	0.20	85.00	7.65	4.03	
Gate Structure	7g.1.3	0.17	91.25	1.91	5.14	C.66
Loading History	7g.1.3.1	0.17	92.50	3.83	5.07	
Cracks	7g.1.3.2	0.17	92.50	3.83	5.07	
Distortion	7g.1.3.3	0.17	92.50	3.83	5.07	
Skin Plate Corrosion	7g.1.3.4	0.17	85.00	7.65	4.03	
Tension/Comp. Corrosion	7g.1.3.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7g.1.3.6	0.17	92.50	3.83	5.07	
Closure Structure (Stop Log, Bulk	7g.1.4	0.17	92.50	1.56	5.25	C.67
Structural Evaluation	7g.1.4.1	0.17	92.50	3.83	5.07	
Cracks	7g.1.4.2	0.17	92.50	3.83	5.07	
Distortion	7g.1.4.3	0.17	92.50	3.83	5.07	
Skin Plate Corrosion	7g.1.4.4	0.17	92.50	3.83	5.07	
Tension/Comp. Corrosion	7g.1.4.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7g.1.4.6	0.17	92.50	3.83	5.07	
Bottom and Side Seals	7g.1.5	0.17	92.50	3.83	5.07	C.68
Ice Prevention	7g.1.6	0.17	92.50	3.83	5.07	C.31
Access and Control	7g.2	0.10	92.50	3.83	5.07	
Remote and Onsite Controls	7g.2.1	1.00	92.50	3.83	5.07	C.23

Derived from a Combination of Inspected Items

Directly Measured by Inspection

Table 5.6: Condition Index and Reliability Results for the Hoist Sub-System on the Great Falls Spillway

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Hoist #1	6c.1		91.85	0.95	5.23	
Power Supply and Controls	7h.1	0.50	92.50	1.61	5.25	
Limit Switches	7h.1.1	0.25	92.50	3.83	5.07	C.30
Motor Control Center	7h.1.2	0.25	92.50	2.21	5.21	C.35
Functional Test	7h.1.2.1	0.33	92.50	3.83	5.07	
Visual Inspection	7h.1.2.2	0.33	92.50	3.83	5.07	
Cabinet Heating	7h.1.2.3	0.33	92.50	3.83	5.07	
Distribution Panel	7h.1.3	0.25	92.50	2.71	5.18	C.32
Functional Test	7h.1.3.1	0.50	92.50	3.83	5.07	
Visual Inspection	7h.1.3.2	0.50	92.50	3.83	5.07	
Cabinet Heating	7h.1.3.3	0.00	N/A	N/A	N/A	
Cam Switches	7h.1.4	0.25	92.50	3.83	5.07	C.36
Functional Test	7h.1.4.1	1.00	92.50	3.83	5.07	
Overheating or Arching	7h.1.4.2	0.00	N/A	N/A	N/A	
Force Transmission	7h.2	0.50	91.20	1.00	5.17	
Split Bush./Journal Bearing	7h.2.1	0.09	92.50	3.83	5.07	C.41
Rotating Shaft	7h.2.2	0.09	90.63	2.53	5.05	C.42
Corrosion	7h.2.2.1	0.25	92.50	3.83	5.07	
Warping or Misalign	7h.2.2.2	0.25	92.50	3.83	5.07	
Cracking	7h.2.2.3	0.25	85.00	7.65	4.03	
Missing bolts or comp	7h.2.2.4	0.25	92.50	3.83	5.07	
Gear Assembly	7h.2.3	0.09	89.50	2.54	4.96	C.43
Noise, vibration, jump	7h.2.3.1	0.20	85.00	7.65	4.03	
Toothwear, contact	7h.2.3.2	0.20	92.50	3.83	5.07	
Anchor	7h.2.3.3	0.20	92.50	3.83	5.07	
Bearing / Bushing Wear	7h.2.3.4	0.20	85.00	7.65	4.03	
Lubricant	7h.2.3.5	0.20	92.50	3.83	5.07	
Wheel, axle and bearings	7h.2.4	0.09	92.50	3.83	5.07	C.58
Lifting Connectors (non-ded)	7h.2.5	0.09	92.50	3.83	5.07	C.46
Lifting Connectors (ded)	7h.2.6	0.09	92.50	3.83	5.07	C.45
Drum Sheaves and Pulleys	7h.2.7	0.09	90.63	2.53	5.05	C.49
Variable of Measureable Wear	7h.2.7.1	0.25	92.50	3.83	5.07	
Corrosion	7h.2.7.2	0.25	85.00	7.65	4.03	
Groove Wear	7h.2.7.3	0.25	92.50	3.83	5.07	
Wire rope Clamps/Anchors	7h.2.7.4	0.25	92.50	3.83	5.07	
Brake (hoist)	7h.2.8	0.09	92.50	3.83	5.07	C.50
Fan Brake	7h.2.9	0.09	92.50	3.83	5.07	C.52
Wire Rope & Connectors	7h.2.10	0.09	92.50	1.91	5.23	C.53
Kinking	7h.2.10.1	0.25	92.50	3.83	5.07	
Corrosion	7h.2.10.2	0.25	92.50	3.83	5.07	
Outer Wire Wear/Breakage	7h.2.10.3	0.25	92.50	3.83	5.07	
Tension	7h.2.10.4	0.25	92.50	3.83	5.07	
Lifting Motor (electric)	7h.2.11	0.09	85.00	3.12	4.57	C.34
Insulators	7h.2.11.1	0.17	85.00	7.65	4.03	
Apparent Temperature	7h.2.11.2	0.17	85.00	7.65	4.03	
Overloading	7h.2.11.3	0.17	85.00	7.65	4.03	
Impaired Ventilation	7h.2.11.4	0.17	85.00	7.65	4.03	
Bearings and Bushings	7h.2.11.5	0.17	85.00	7.65	4.03	
Noise and Vibrations	7h.2.11.6	0.17	85.00	7.65	4.03	

Table 5.7: Condition Index and Reliability Results for the Higher Level Sub-Systems, Systems and Spillway Structure on the Great Falls Spillway

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Supporting Items
Level 2: Dam Safety Functions						
Overtopping Design Flood	2a		84.02	0.90	4.61576	4a, 4b
Level 3: Type of Gate						
Level 4: Operational Sys. and Equip.						
Operations	4a	0.3	70.26	2.45	3.48447	5a, 5b, 5c
Equipment	4b	0.7	89.92	0.73	5.08116	5d, 5e
Level 5: Systems						
Gathering Information	5a	0.35	76.72	2.01	4.00574	sep. sheet
Decision Process	5b	0.55	62.10	4.27	2.75826	sep. sheet
Access and Operation	5c	0.1	92.50	1.43	5.25897	sep. sheet
Electrical	5d	0.4	87.26	1.75	4.83613	6a, 6b
Hoist / Gate System	5e	0.6	91.69	0.37	5.22615	6c, 6d, 6e
Level 6: Sub-Systems						
Power Supply	6a	0.40	86.25	2.07	4.74019	sep. sheet
Cables and Controls	6b	0.6	87.94	2.57	4.83719	sep. sheet
Gate-Hoist Sub-System	6cd	0.95	91.65	0.38	5.22275	6cd.1-4
Hoist 1 / Gate 1	6cd.1	0.25	91.58	0.80	5.20956	6c.1, 6d.1
Hoist 2 / Gate 2	6cd.2	0.25	91.67	0.73	5.21812	6c.2, 6d.2
Hoist 3 / Gate 3	6cd.3	0.25	91.67	0.73	5.22	6c.3, 6d.3
Hoist 4 / Gate 4	6cd.4	0.25	91.67	0.73	5.22	6c.4, 6d.4
Hoist 1	6c.1	0.80	91.85	0.95	5.23	sep. sheet
Hoist 2	6c.2	0.80	92.19	0.85	5.26	sep. sheet
Hoist 3	6c.3	0.80	92.19	0.85	5.26	sep. sheet
Hoist 4	6c.4	0.80	92.19	0.85	5.26	sep. sheet
Gate 1	6d.1	0.20	90.48	1.25	5.11	sep. sheet
Gate 2	6d.2	0.20	89.57	1.35	5.03	sep. sheet
Gate 3	6d.3	0.20	89.57	1.35	5.03	sep. sheet
Gate 4	6d.4	0.20	89.57	1.35	5.03	sep. sheet
Supporting Structure	6e	0.05	92.50	2.07	5.22	sep. sheet

Derived from a Combination of Inspected Items

Directly Measured by Inspection

Table 5.8: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components on the Gathering Information, Decision Process, and Access and Operations Systems of the Great Falls Spillway

Item	Component pf	System pf Current Proposal	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Gathering Information		3.09264E-05	0.28686493	0.097689389
River Flow Measurement		9.60546E-06	0.014715658	0.014715263
Water Level Indicator	2.00486E-07			
Data Acquisition Device	2.00486E-07			
Data Transmission	0.014715263			
Reservoir Level Indicator		9.60546E-06	0.014715658	0.014715263
Water Level Indicator	2.00486E-07			
Data Acquisition Device	0.014715263			
Data Transmission	2.00486E-07			
Precipitation & Temp. Gauge		4.78599E-05	0.097689751	0.097689389
Precip & Temp Gauges	0.097689389			
Data Acquisition Device	2.00486E-07			
Data Transmission	2.00486E-07			
Snow Measuring Model	0.097689389			
Flow Predicition Model	0.097689389			
Weather Forecasting	4.32368E-05			
Ice and Debris Management		9.24035E-08	6.01459E-07	2.00486E-07
Monitoring	2.00486E-07			
Management	2.00486E-07			
Control Equipment	2.00486E-07			
Gate Position Indicator		9.24035E-08	6.01459E-07	2.00486E-07
Position Indicator	2.00486E-07			
Data Acquisition Device	2.00486E-07			
Data Transmission	2.00486E-07			
Third-Party Flow Data	2.00486E-07			
Decision Process		0.002905596	0.221251349	0.097689389
Data Processing	2.00486E-07			
Analysis	0.097689389			
Decision Process	0.097689389			
Public Protection Warning System	0.014715263			
Operation Procedures		0.006890764	0.029213987	0.014715263
Standard Operating Procedures	0.014715263			
Autonomous Operating Proc.	0.014715263			
Access and Operations		7.25771E-08	1.60389E-06	2.00486E-07
Avail. and Mobilization (Load Rejection)		1.13071E-07	4.00973E-07	2.00486E-07
Availablity	2.00486E-07			
Mobilization	2.00486E-07			
Avail. and Mobilization (Load Rejection)		1.13071E-07	4.00973E-07	2.00486E-07
Availablity	2.00486E-07			
Mobilization	2.00486E-07			
Qualification / Training of Operator	2.00486E-07			
Local Access		1.13071E-07	4.00973E-07	2.00486E-07
Pedestrian Access	2.00486E-07			
Keys and Locks	2.00486E-07			
Lighting System	2.00486E-07			

Table 5.9: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components on the Power Supply, Cables and Controls, and Supporting Structure Sub-Systems on the Great Falls Spillway

Item	Component pf	System pf Current Proposal	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Power Supply		1.06889E-06	0.000275091	2.74724E-05
Local or Emergency Generators		1.06889E-06	0.000275091	2.74724E-05
Frequency and Voltage	2.74724E-05			
Engine Temperature / Oil Pressure	2.74724E-05			
Starting Sequence	2.74724E-05			
Noise and Vibratiion	2.74724E-05			
Functional Test	2.00486E-07			
Fuel	2.00486E-07			
Batteries	2.74724E-05			
Battery Charger	2.74724E-05			
Alternator	2.74724E-05			
Lubrication	2.74724E-05			
Cooling System	2.74724E-05			
Intake and Exhaust System	2.74724E-05			
Cables and Controls		6.59336E-07	0.000165024	2.74724E-05
Underground and Encased Cables		7.44806E-06	5.49441E-05	2.74724E-05
Insulation	2.74724E-05			
Terminators	2.74724E-05			
Power Feeder Cables		7.44806E-06	5.49441E-05	2.74724E-05
Insulation	2.74724E-05			
Terminators	2.74724E-05			
Transformer		2.11036E-06	5.49441E-05	2.74724E-05
Dielectric	N/A			
Insulation	2.74724E-05			
Windings	2.74724E-05			
Tank	N/A			
Power Source Transfer System		2.00486E-07	2.00486E-07	2.00486E-07
Test (Transfer Switch)	N/A			
Test (Manual Transfer Device)	2.00486E-07			
Supporting Structure		8.77766E-08	1.60389E-06	2.00486E-07
Lifting Device Structure (Steel)		7.50719E-08	1.4034E-06	2.00486E-07
Displacement / Deterioration	2.00486E-07			
Anchor Bolts	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Lifting Device Structure (Concrete)	2.00486E-07			

Table 5.10: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components on the Gate Sub-Systems on the Great Falls Spillway

Item	Component pf	System pf Current Proposal	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Gate #1		1.61924E-07	0.016027391	0.014715263
Gate Structure and Support		1.74709E-07	0.016027194	0.014715263
Approach and Exit Channel		7.82941E-08	1.00243E-06	2.00486E-07
Loss of Concrete Apron	2.00486E-07			
Loss of Concrete Pier/Base	2.00486E-07			
Scour of Foundation	2.00486E-07			
Upstream Sedimentation	2.00486E-07			
Downstream Blockage	2.00486E-07			
Embedded Parts		1.34074E-05	0.01599661	0.014715263
Gate Lifting Effort	2.00486E-07			
Geometrical Alignment Roller	0.014715263			
Roller Path Corrosion	0.001272646			
Roller Tooth Wear	2.00486E-07			
Corrosion Remainder	2.74724E-05			
Gate Structure		1.40177E-07	2.84748E-05	2.74724E-05
Loading History	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Skin Plate Corrosion	2.74724E-05			
Tension/Comp. Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Closure Structure (Stop Log, Bulkheads)		7.50719E-08	1.20292E-06	2.00486E-07
Structural Evaluation	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Skin Plate Corrosion	2.00486E-07			
Tension/Comp. Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Bottom and Side Seals	2.00486E-07			
Ice Prevention	2.00486E-07			
Access and Control		2.00486E-07	2.00486E-07	2.00486E-07
Remote and Onsite Controls	2.00486E-07			

Table 5.11: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components on the Hoist Sub-Systems on the Great Falls Spillway

Item	Component pf	System pf Current Proposal	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Hoist #1		8.63914E-08	0.0005002	2.74724E-05
Power Supply and Controls		7.60663E-08	1.4034E-06	2.00486E-07
Limit Switches	2.00486E-07			
Motor Control Center		9.24035E-08	6.01459E-07	2.00486E-07
Functional Test	2.00486E-07			
Visual Inspection	2.00486E-07			
Cabinet Heating	2.00486E-07			
Distribution Panel		1.13071E-07	4.00973E-07	2.00486E-07
Functional Test	2.00486E-07			
Visual Inspection	2.00486E-07			
Cabinet Heating	N/A			
Cam Switches		2.00486E-07	2.00486E-07	2.00486E-07
Functional Test	2.00486E-07			
Overheating or Arching	N/A			
Force Transmission		1.14401E-07	0.000498797	2.74724E-05
Split Bush./Journal Bearing	2.00486E-07			
Rotating Shaft		2.25238E-07	8.36179E-05	2.74724E-05
Corrosion	2.00486E-07			
Warping or Misalign	2.00486E-07			
Cracking	2.74724E-05			
Missing bolts or comp	2.00486E-07			
Gear Assembly		3.53813E-07	5.55455E-05	2.74724E-05
Noise, vibration, jump	2.74724E-05			
Toothwear, contact	2.00486E-07			
Anchor	2.00486E-07			
Bearing / Bushing Wear	2.74724E-05			
Lubricant	2.00486E-07			
Wheel, axle and bearings	2.00486E-07			
Lifting Connectors (non-ded)	2.00486E-07			
Lifting Connectors (ded)	2.00486E-07			
Drum Sheaves and Pulleys		2.25238E-07	2.80739E-05	2.74724E-05
Variable of Measureable Wear	2.00486E-07			
Corrosion	2.74724E-05			
Groove Wear	2.00486E-07			
Wire rope Clamps/Anchors	2.00486E-07			
Brake (hoist)	2.00486E-07			
Fan Brake	2.00486E-07			
Wire Rope & Connectors		8.33506E-08	0.000165625	2.00486E-07
Kinking	2.00486E-07			
Corrosion	2.00486E-07			
Outer Wire Wear/Breakage	2.00486E-07			
Tension	2.00486E-07			
Lifting Motor (electric)		2.45357E-06	0.000164823	2.74724E-05
Insulators	2.74724E-05			
Apparent Temperature	2.74724E-05			
Overloading	2.74724E-05			
Impaired Ventilation	2.74724E-05			
Bearings and Bushings	2.74724E-05			
Noise and Vibrations	2.74724E-05			

Table 5.12: Comparison of the Currently Proposed CI System Probability of Failure and the Traditional System Reliability Approach for both Independent and Perfectly Correlated Components on the Higher Level Sub-Systems, Systems and Spillway Structure on the Great Falls Spillway

Item	System pf Current Proposal	System pf Statistical Independence	System pf Perfect Correlation
Level 2: Dam Safety Functions			
Overtopping Design Flood	1.96034E-06	0.444893242	0.097689389
Level 3: Type of Gate			
Level 4: Operational Sys. and Equip.			
Operations	0.000246599	0.444647917	0.097689389
Equipment	1.87888E-07	0.000441747	0.014715263
Level 5: Systems			
Gathering Information	3.09264E-05	0.28686493	0.014715263
Decision Process	0.002905596	0.221251349	0.097689389
Access and Operation	7.25771E-08	1.60389E-06	2.00486E-07
Electrical	6.6284E-07	0.00044007	2.74724E-05
Hoist / Gate System	8.67067E-08	1.67836E-06	0.014715263
Level 6: Sub-Systems			
Power Supply	1.06889E-06	0.000275091	2.74724E-05
Cables and Controls	6.59336E-07	0.000165024	2.74724E-05
Gate-Hoist Sub-System	8.83125E-08	7.44724E-08	0.014715263
Hoist 1 / Gate 1	9.48291E-08	0.016519574	0.014715263
Hoist 2 / Gate 2	9.05476E-08	0.016519574	0.014715263
Hoist 3 / Gate 3	9.05476E-08	0.016519574	0.014715263
Hoist 4 / Gate 4	9.05476E-08	0.016519574	0.014715263
Hoist 1	8.63914E-08	0.0005002	2.74724E-05
Hoist 2	7.36896E-08	0.0005002	2.74724E-05
Hoist 3	7.36896E-08	0.0005002	2.74724E-05
Hoist 4	7.36896E-08	0.0005002	2.74724E-05
Gate 1	1.61924E-07	0.016027391	0.014715263
Gate 2	2.40621E-07	0.016027391	0.014715263
Gate 3	2.40621E-07	0.016027391	0.014715263
Gate 4	2.40621E-07	0.016027391	0.014715263
Supporting Structure	8.77766E-08	1.60389E-06	2.00486E-07

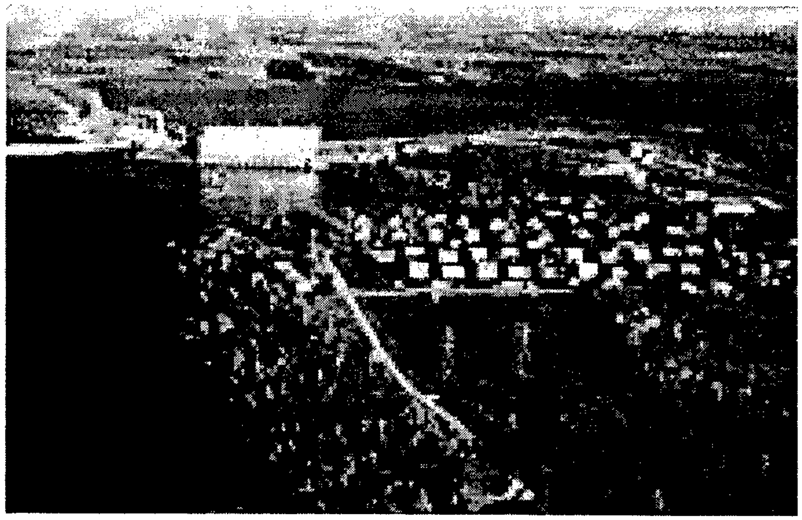

Figure 5.1: Photograph of the Great Falls Dam on the Winnepeg River (Manitoba Hydro 2004)

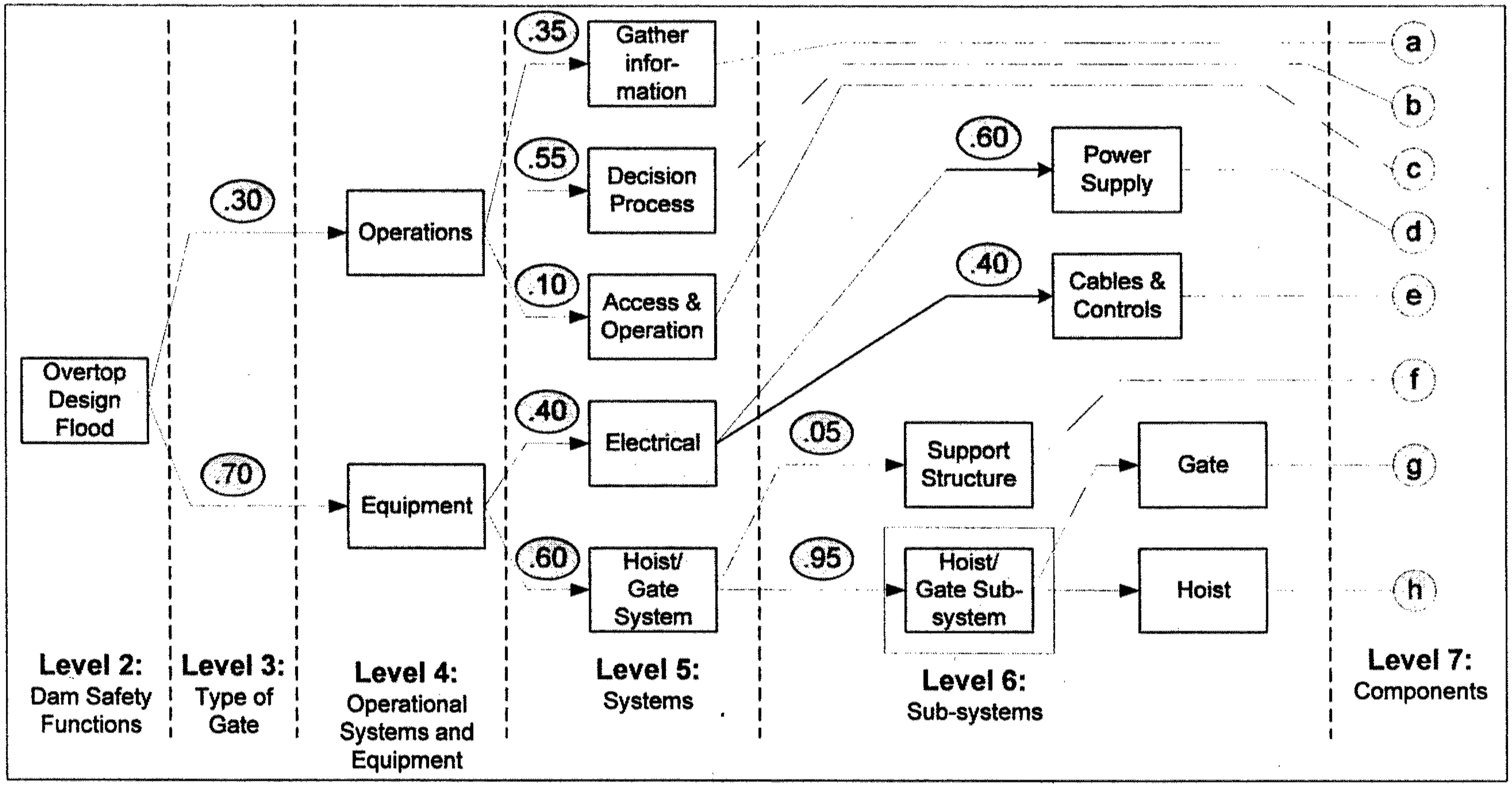

Figure 5.2: The Seven Level Hierarchy of Systems, Sub-Systems and Components that Comprise the Great Falls Dam

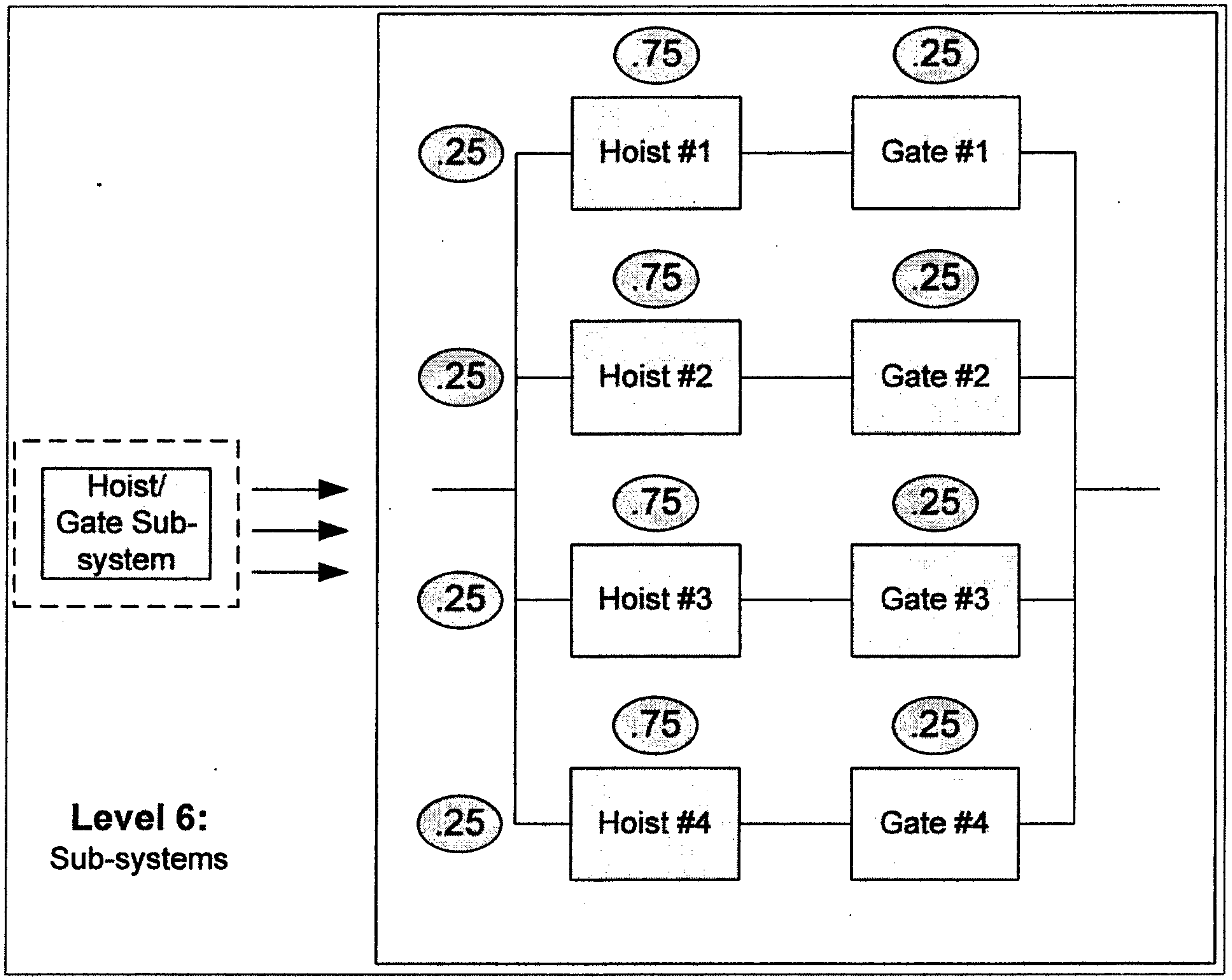

Figure 5.3: The Hoist/Gate Sub-System Modeled as a Parallel-Series System of the Four Separate Gates Which Each Have a Dedicated Hoist

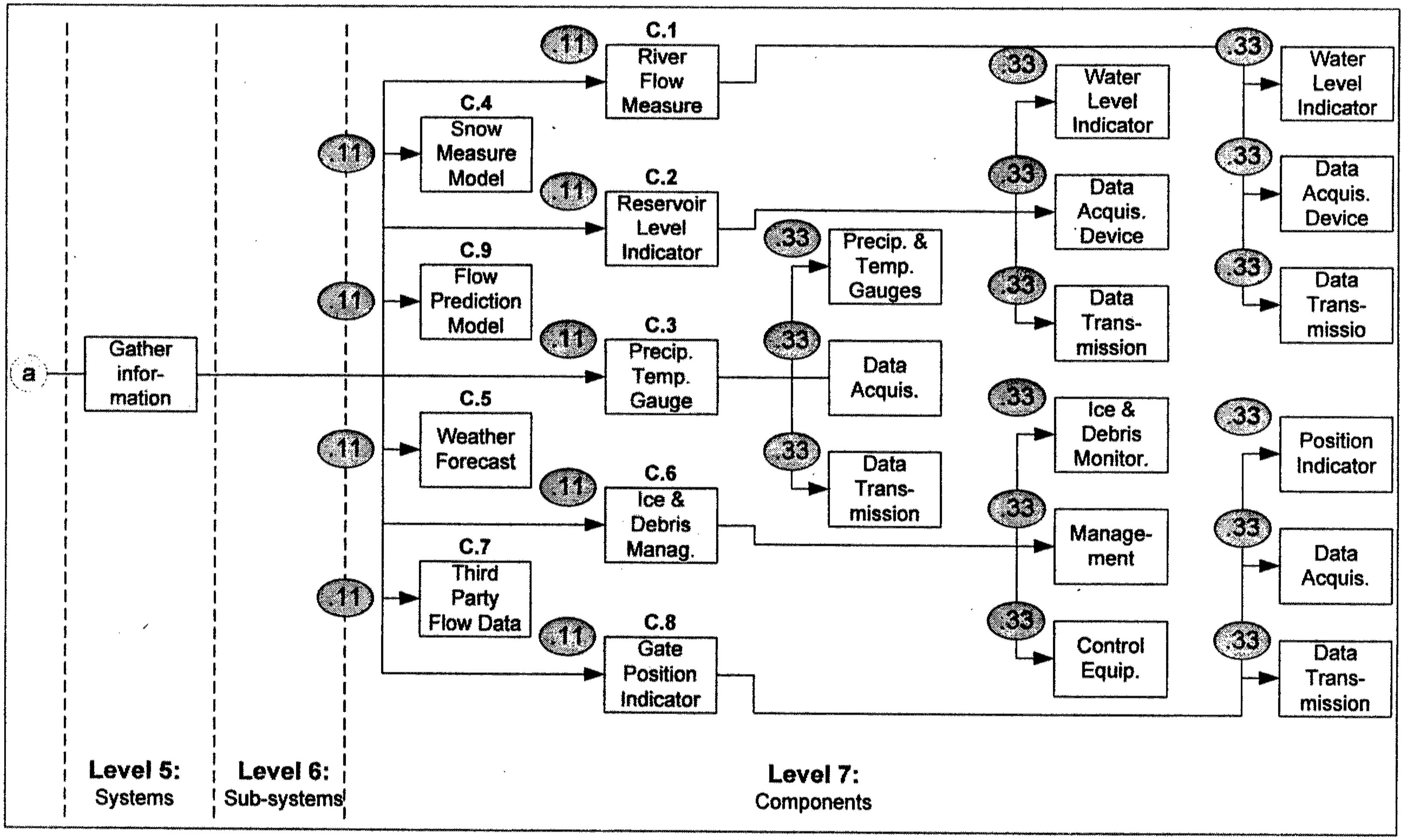

Figure 5.4: The Components and Sub-Components of the Gathering Information System on the Great Falls Dam

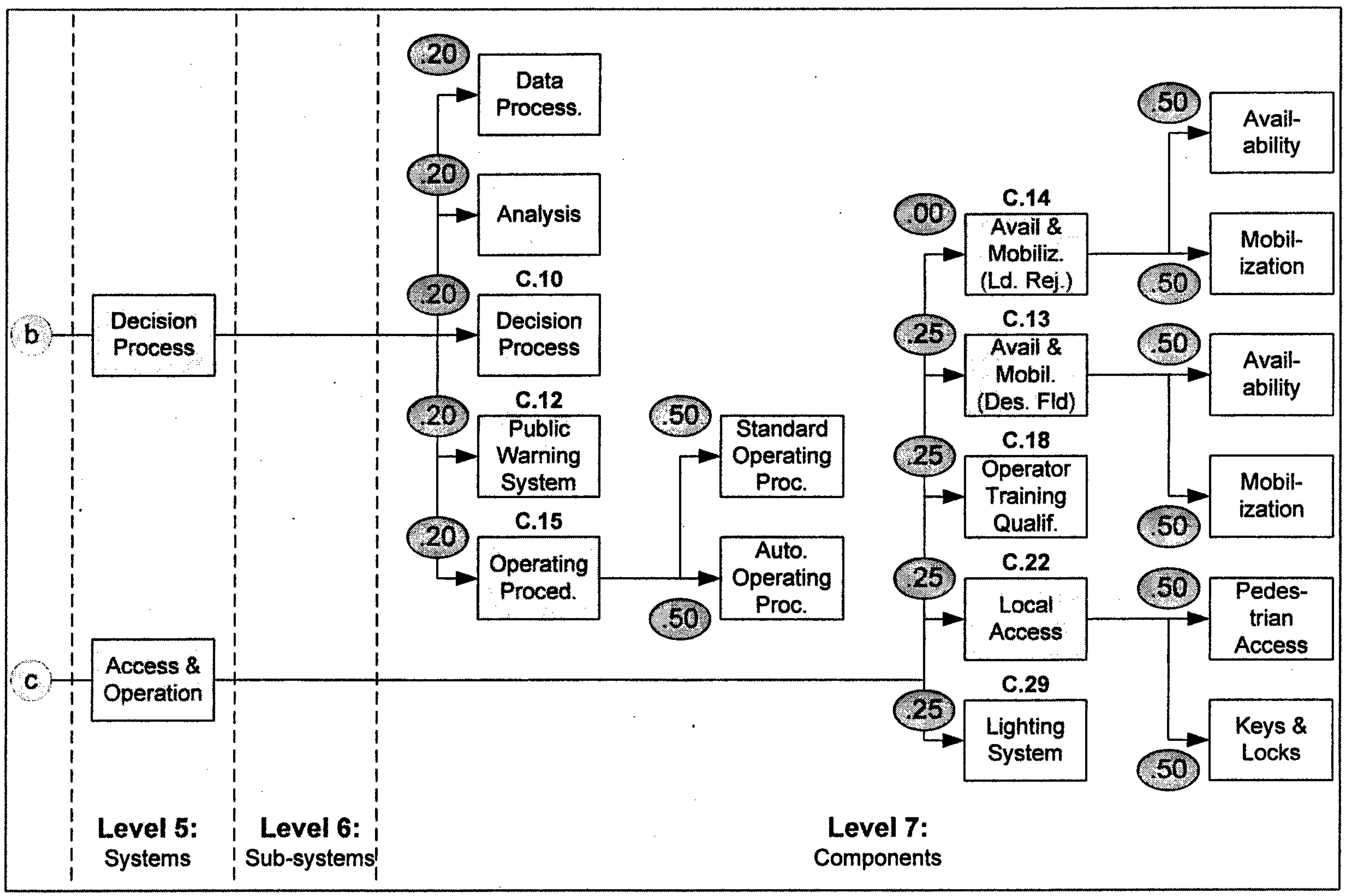

Figure 5.5: The Components and Sub-Components of the Decision Process and the Access and Operations Systems on the Great Falls Dam

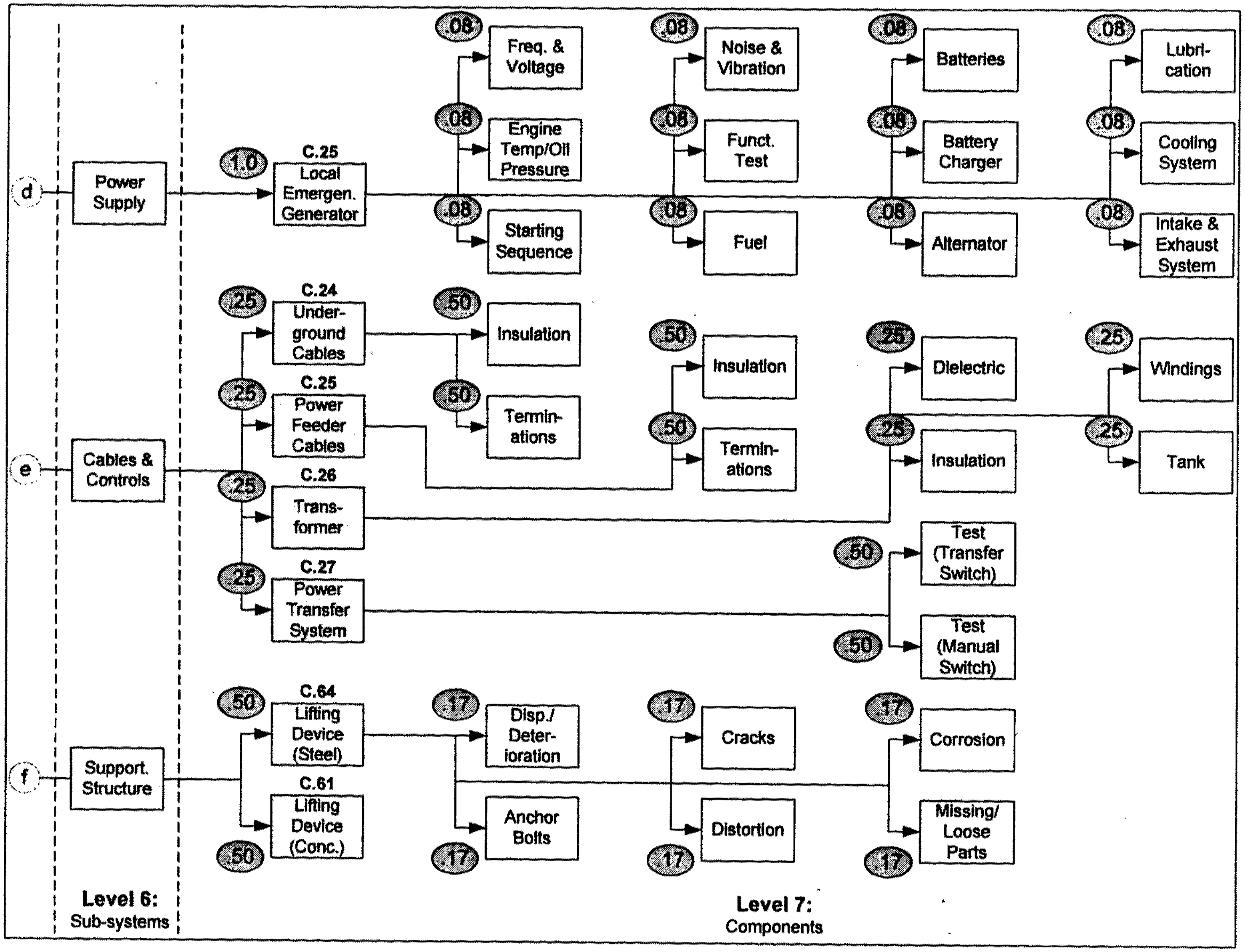

Figure 5.6: The Components and Sub-Components of the Power Supply, Cables and Controls, and Support Structure Systems on the Great Falls Dam

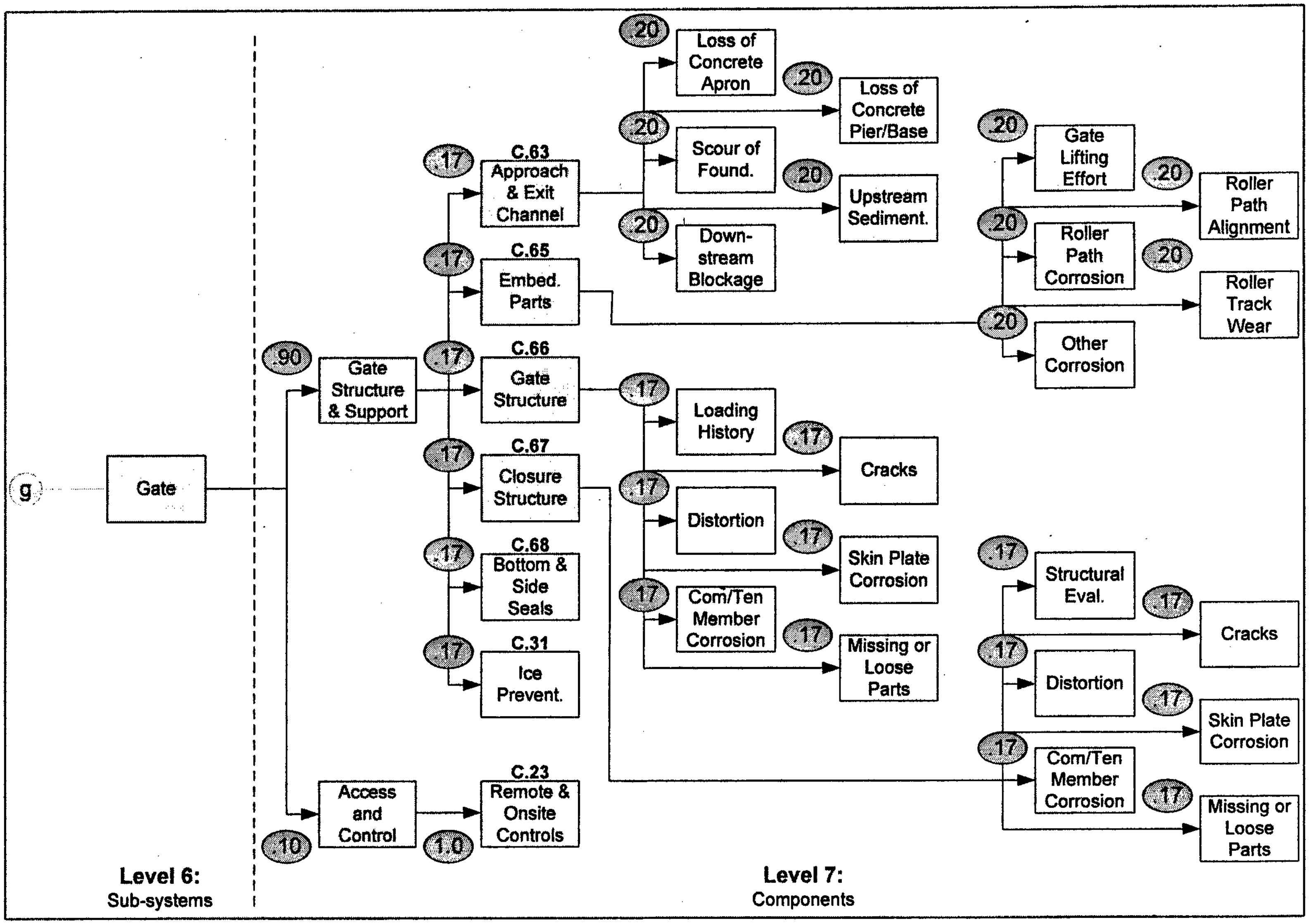

Figure 5.7: The Components and Sub-Components of the Gate System on the Great Falls Dam

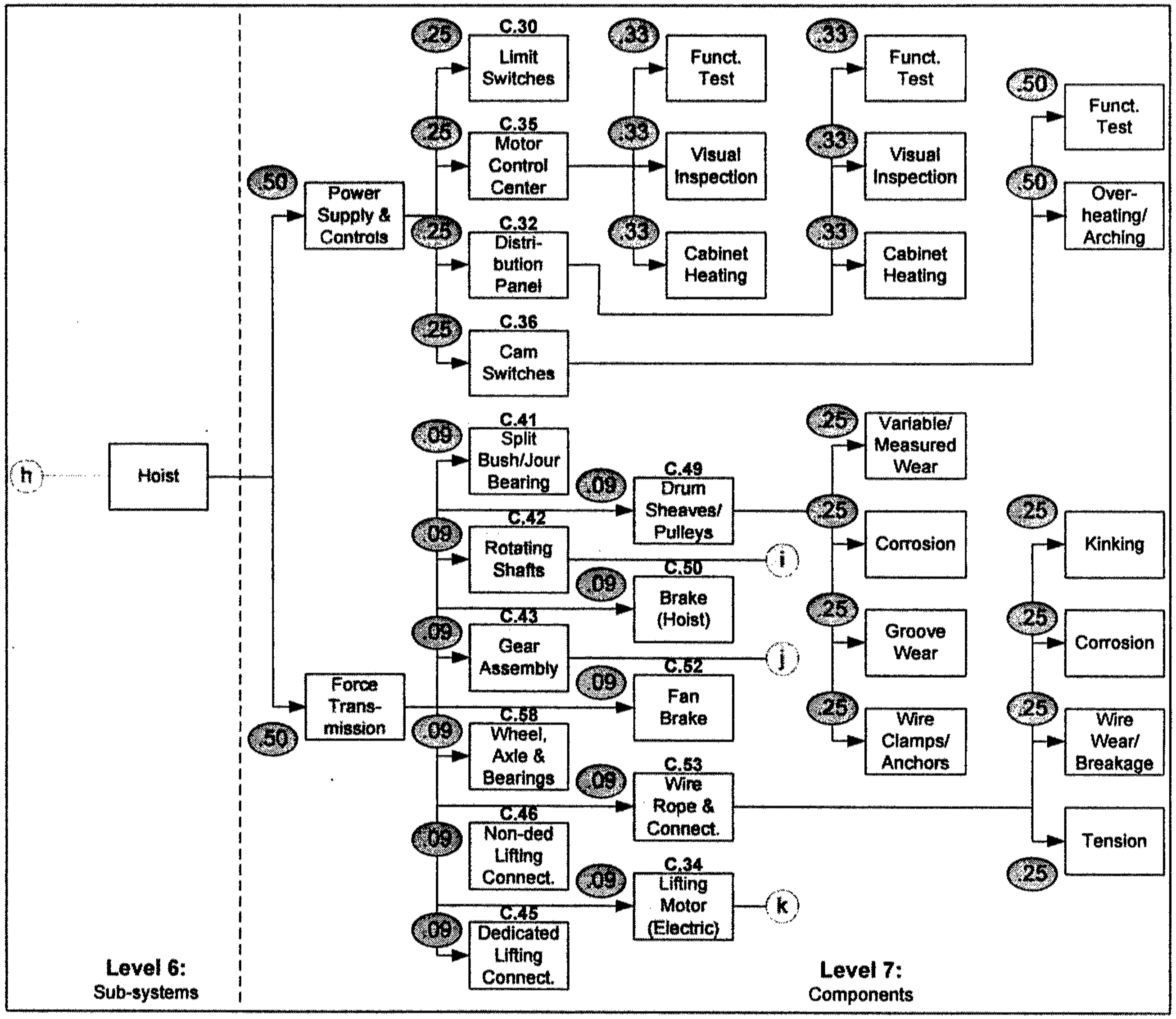

Figure 5.8: The Components and Sub-Components of the Hoist System on the Great Falls Dam

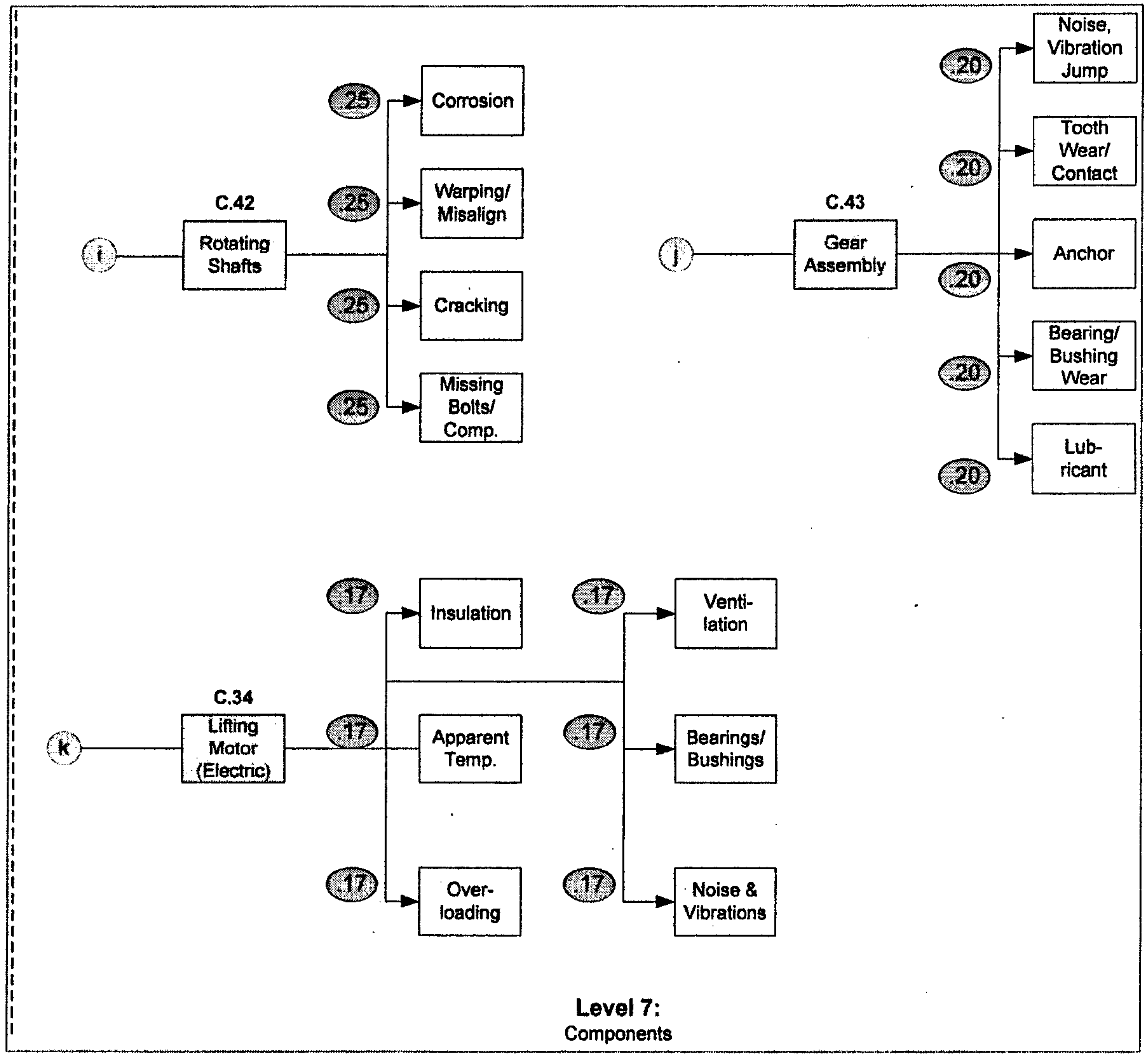

Figure 5.9: Additional Components and Sub-Components of the Hoist System on the Great Falls Dam

Chapter 6: Incorporating Structural Vulnerability

6.1 Background

Security of the Nation's infrastructure has always been an important concern, but never more so since the terrorist attacks of September 11, 2001. Upgrading the security of various structures has become a major source of maintenance and rehabilitation funding. The American Waterworks Association (AWWA 2003) estimates that it will require $500 million for vulnerability assessments and $1.6 billion for security protection for the nation's utilities. The Bureau of Reclamation spent $33 million in 2002 and $53 million in 2003 on vulnerability assessment and security projects on its high priority dams. As such, the vulnerability of a structure to terrorist attack could be a relevant consideration in the condition assessment of a structure. The proposed condition index methodology is flexible enough to incorporate any relevant variable. The purpose of this chapter is to illustrate how structural vulnerability can be incorporated into the development of a structure's condition index.

6.2 Incorporating Security into the Condition Index

Using the hypothetical structure from Fig. 4.4, Fig. 6.1 adds a Security system to the structure and provides an importance value relative to the rest of the structure. The importance values of the rest of the structure must be reduced to allow the sum of importance factors at a given level to equal 1.0. Assume the Security system was given a rating where the mean CI was 70 and the standard deviation was 7.4. Eq. 4.10 revealed that the original structure's mean CI value was 89.5 with a standard deviation of 3.16 at year 0. Incorporating a Security system into the structure with the score indicated, the structural system CI would become:

$$CI_{System,Year0} = (0.16)(85) + (0.48)(92.5) + (0.16)(85) + (0.2)(70) = 85.6 \tag{6.1}$$

$$\sigma_{System,Year0} = \sqrt{(0.16)^2(7.65)^2 + (0.48)^2(3.83)^2 + (0.16)^2(7.65)^2 + (0.2)^2(7.4)^2} = 2.93$$

As a result of the Security rating, the overall Structure CI was slightly less and would make the structure a slightly more likely candidate for maintenance upgrade funding. The magnitude of the effect is determined by the importance factor given to security.

The security rating is deliberately kept separate from the rest of the structure to give the analyst the option of easily including or excluding it from the analysis. As with the Great Fall Spillway, it would have been easy to separate the Equipment system from the Operations system if the analyst preferred to only consider the Equipment. The Security system rating could be treated as a component where a simplistic and subjective high, medium or low rating could form a component condition table. Conversely, it could be a complex and comprehensive system consisting of many components and sub-components. Fig. 6.2 suggests a sample hierarchical structure for a security system.

The Security system is divided into sub-systems reflecting the Criticality, Redundancy, Vulnerability and Response Planning aspects of the structure. The Criticality accounts for the effects on the community and economy if the structure is immobilized. It could be measured in terms of dollar consequence of destruction, anticipated lives lost, dollar value of commerce lost, or size of population affected. The

Redundancy sub-system assesses the ability of a single fire, bomb, or power loss to destroy or shut down the entire structure. Alternative power sources, multiple lift gates, or redundant structural members might be critical considerations. Response Planning reflects the ability of the community and people on site to respond to an attack and is further sub-divided into internal and external capabilities. Internal Planning capabilities measure the capability of the site personnel to respond and will be assessed using criteria such as response standard operating procedures, training programs, internal drills and rehearsals, redundant and reliable communication equipment, early warning procedures, detection capabilities, alarm systems, and reporting procedures. The External Planning assesses the response capability of the outside community to include law enforcement, fire fighters, medical teams, and local, state, and federal response teams. Access and distance to the site are also included.

Structure Vulnerability refers to the ease with which the site can be attacked. Fig. 6.2 further classifies Vulnerability in terms of air, water, land, and cyberspace. Attack from the air might include chemical or biological attack, dropping a bomb, or flying an airplane into the structure. The Vulnerability assessment would be a function of local air defense, air traffic patterns, and ability of the structure to withstand a hit. For dams, a water attack might include assault by watercraft or simply the ability of a terrorist to float an explosive device downstream. Vulnerability would be assessed by protective measures such as boat patrols that could observe and intercept attacks, observation capability, and ability of the structure to withstand attack. Cyberspace Vulnerability would depend on the structure's degree of reliance on computers and computer systems.

Vulnerability might be determined by the security of the computer systems, redundancy, access to terminals, and the use of firewalls, intrusion detection devices, and password protection.

The most common threat is probably coming by land. The Land sub-system is divided into the Power Supply, Communications and Site Security components. The Site Security component consists of Access, Observation and Presence sub-components. Access measures the ability to control who is allowed on the site. It might include a perimeter fence; keys or badges to control access; locks on doors and gates; procedures for contractors, deliveries or tour groups; and hardened doors and windows. Observation incorporates the ability to see and detect any terrorist activity. The existence of lighting systems, video cameras, and roving patrols would enhance situation awareness. Along the same line, chemical alarms, radar systems, and bomb-sniffing dogs would detect potential threats. The remote nature of a site might affect observation by the general population. Fig. 6.3 shows photographs of some security devices currently in place on locks and dams.

Finally, Presence measures the degree to which site personnel are available to protect the site. The lowest level of the hierarchy contains an inspectable item with a component condition table where the inspector must attempt to match the actual situation to the best description on the table. Table 6.1 suggests a sample Component Condition Table for the Site Presence sub-component of the Site Security component. In this example, the CI score for Presence is a function of hours of operation, guards on site, and the hiring of a Security Manager. The Security system CI score is a function of the inspection CI scores and importance factors of all the sub-levels that comprise the system using the same approach outlined in Chapter 3.

The Security system presented in this report is just one example of the many possibilities. The Corps of Engineers has invested in the Risk Assessment Methodology for Dams (RAM-D) whose purpose is to identify and counter the potential threat to the nation's 75,000 dams (Matalucci, 2002). The results obtained from RAM-D analyses could be incorporated into the CI ratings. Whatever method is used to evaluate the security and vulnerability status of a structure, it appears that it can easily be incorporated into a condition index assessment of a structure if the manager feels it is relevant.

Table 6.1: A Sample Component Condition Table for the Site Presence Sub-component of the Site Security Component of the Security System on the Hypothetical Structure in Figures 6.1 and 6.2

Site Presence								
Function								
Excellent	Sufficient personnel on site at all times to observe and deter potential threats							
Failed	Site has insufficient personnel to provide adequate awareness of threats							
	0 – 9	10 – 24	25 – 39	40 – 54	55 – 69	70 – 84	85 – 100	Comments
Indicator	1	2	3	4	5	6	7	
(1) 24 hour operations; personnel constantly on site; (2) dedicated security manager; (3) guards posted at gates							X	
(1) 24 hour operations; personnel constantly on but gate guards have 24 hour presence						X		
24 hour operations; neither 2 nor 3 from above OR personnel on site during normal business hours but gate guards have 24 hour presence					X			
personnel on site only during business hours; no gate guards or security manager			X	X				
site is unmanned, but located in a populated area		X						
site is unmanned and located in a remote area	X							

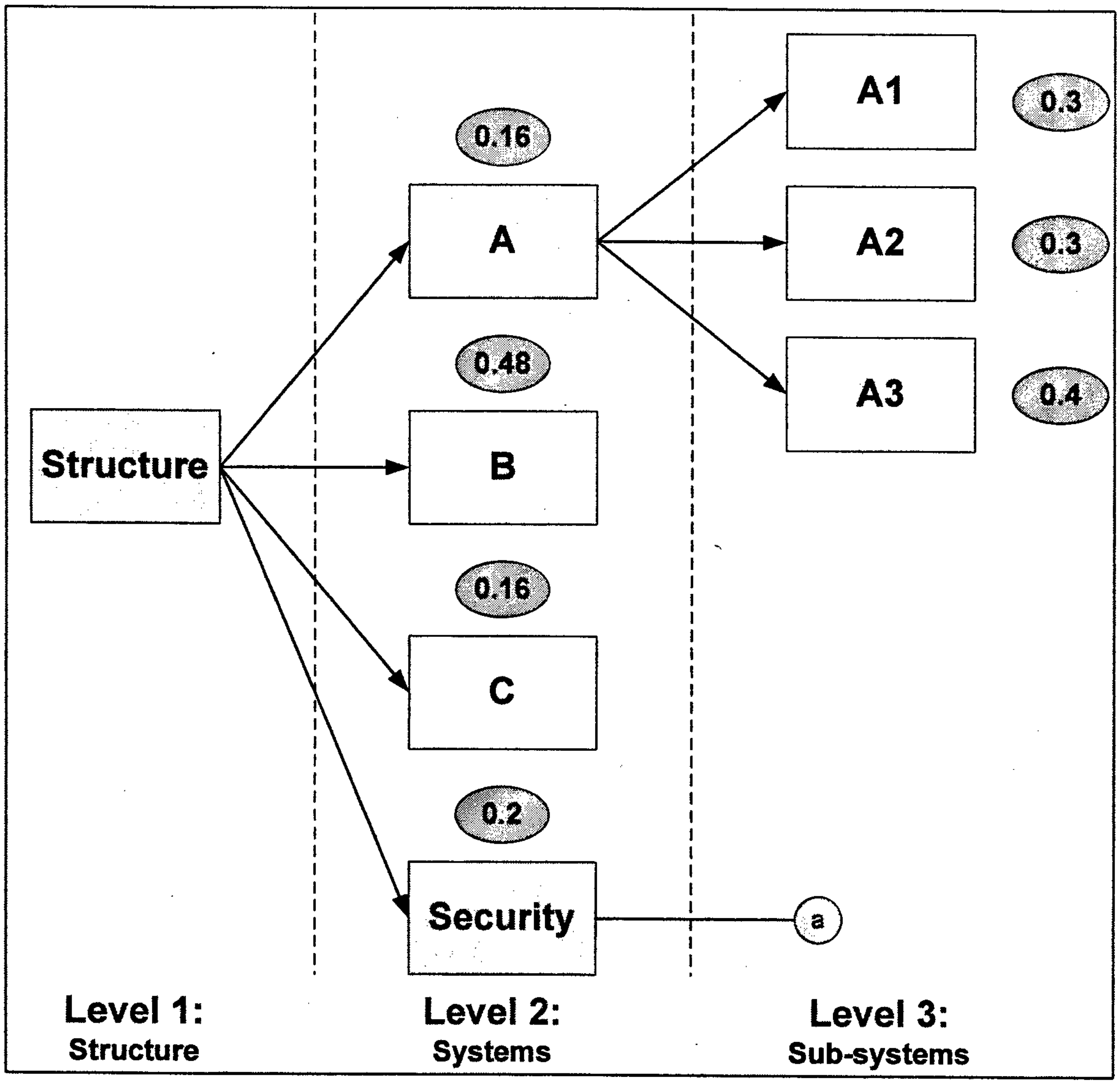

Figure 6.1: Structural Hierarchy of the Hypothetical Structure From Figure 4.4 Where a Security System is Included in the Condition Index Analysis

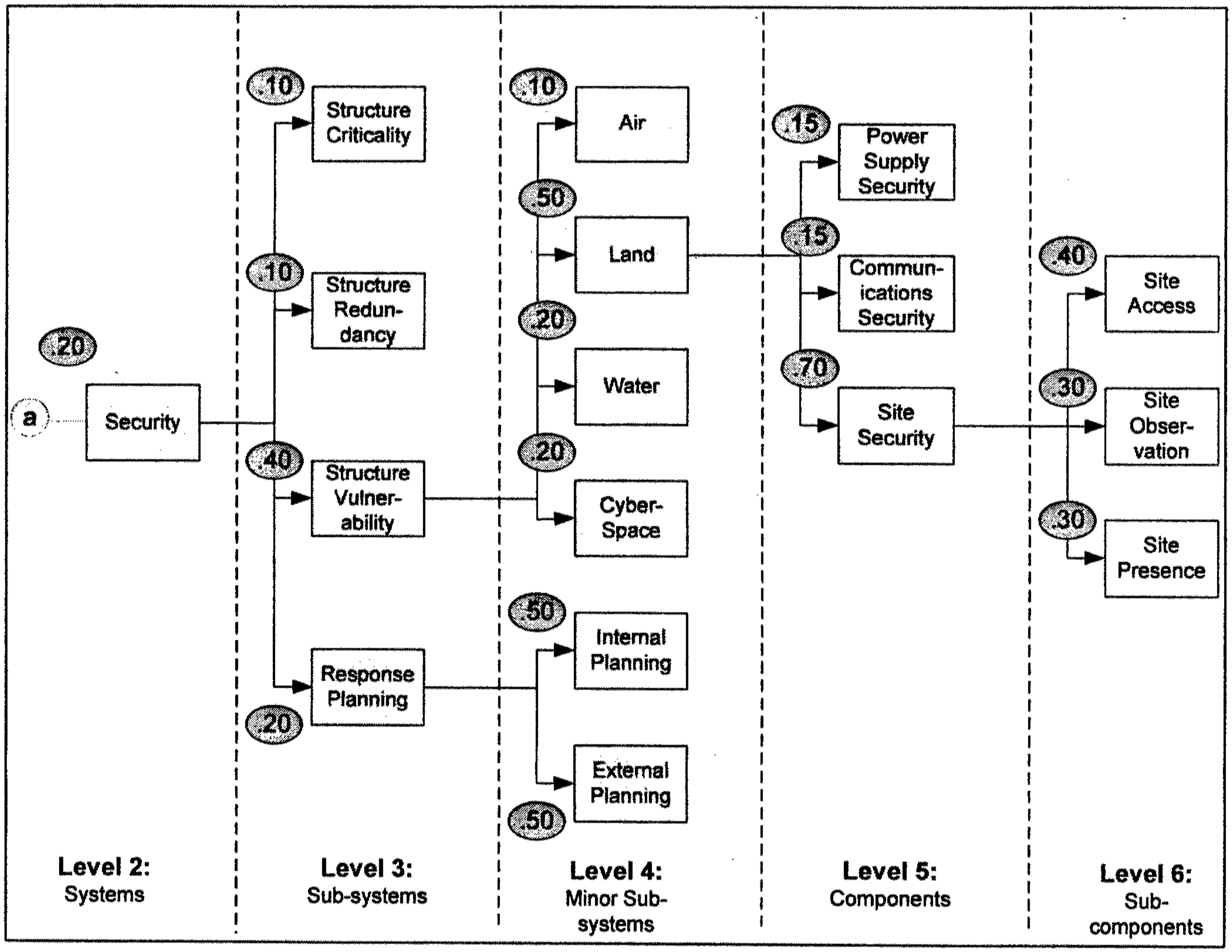

Figure 6.2: Security System for Hypothetical Structure with Selected Sub-Systems and Components

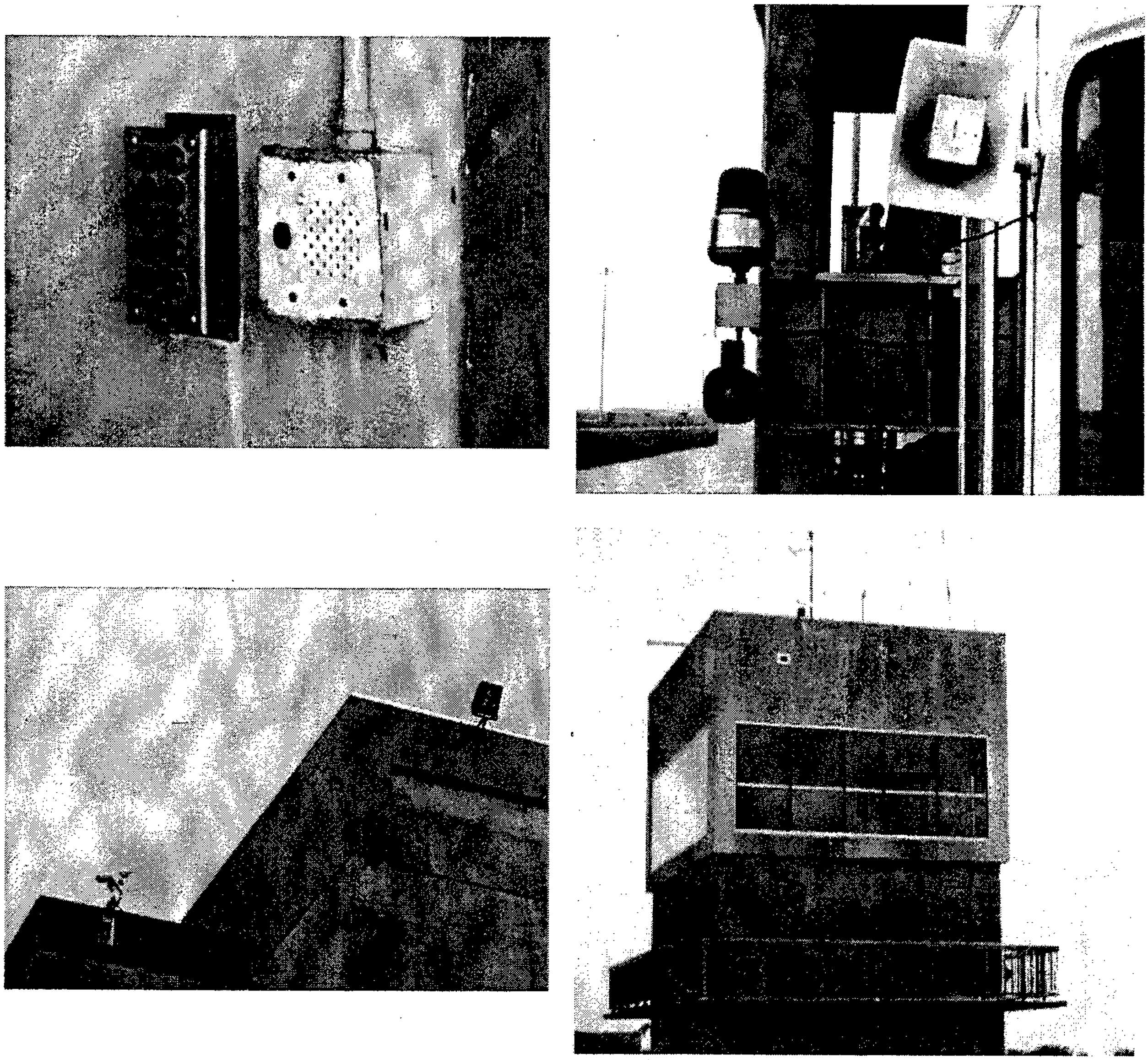

Figure 6.3: Photographs of Security Measures Taken on a Lock and Dam Structure to Include Coded Locks, Intercom System, Alarm Systems, Closed Circuit Cameras, Lighting Systems, and an Observation Tower (Photos taken by the Author)

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

This report has introduced a probabilistic approach for condition index assessment of structures that will allow a type of risk-based analysis based on periodic visual inspection results. The report provided background information and an explained why the issue was important. The current methods for deterministic condition index assessment and reliability analyses of both civil and mechanical/electrical structures were discussed. After covering the challenges associated with applying risk-based methods to condition index data, a proposed methodology was introduced using a simple hypothetical series-parallel structure as an example. Key assumptions were introduced that covered the definition of failure, the probabilistic parameters of the condition states, and the linear transition through condition states. It was assumed that all components were statistically independent, normally distributed random variables and that any structure can be described as a hierarchy of systems, sub-systems and components. Higher level CI values were obtained from component inspection results and the relative importance of components to the overall structure. The reliability index and probability of failure were computed at various points in time, along with a cost-benefit analysis using the hazard function. Examples showed that the initial assumptions can be updated over time using as actual inspection data becomes available.

The probabilistic approach was applied to spillways on dams using Chouinard *et.al.* (2003) as the source for the structural hierarchy, importance factors, and component condition tables. After covering how spillways work, how a traditional reliability analysis is done, and how the deterministic CI is performed, the proposed approach was applied to the Great Falls Spillway using the actual inspection data. The differences between treating the structural system as a composite or weighted average of its components versus the traditional system reliability analysis of series and parallel systems was discussed and illustrated.

Finally, security and vulnerability issues were incorporated into the CI analysis. The CI approach is flexible enough to accommodate any relevant variables, even if they are difficult to quantify. A sample Security system was added to the previous hypothetical structure to illustrate how terrorism issues can be included. The approach is based on CI data, is probabilistic in nature, and allows a risk-based approach to overall structural condition. The proposed methodology has certain strengths and limitations that bear mention.

7.1.1 Strengths

The benefits of the approach described in this report include:

- Based on the assumptions made, a risk-based analysis using the well established methods of a reliability index, probability of failure, hazard function, and cost-benefit analysis is possible.
- The methodology is based on the deterministic CI methods already published. This means any inspection data that already exists using such methods can be used without modification with the techniques described in this report.

- A structure is described in strict hierarchical form. The analysis is easily broken down by component and portions of the structural system can easily be excluded or included based on the desire of the analyst. All levels of the hierarchy are visible making it easier to identify which components most affect a system rating and to evaluate alternatives of replacing a component versus replacing an entire structure. This study used the hierarchy to a fuller degree that Chouinard *et.al.* (2003) by including importance factors at the component and sub-component level.
- The inspector is only required to choose the appropriate condition state for a component based on the component condition tables. The actual CI mean value is determine by how long the component has been in that condition state. Chouinard *et.al.* (2003) required the inspector to produce an actual CI value which becomes highly subjective and will vary greatly between inspectors, especially if the condition state has a large range of values. The proposed method will provide greater consistency between inspectors.
- Based on the assumed capability of the inspector, the uncertainty of the inspection reading is quantified. In a deterministic approach, a CI rating is given the same credibility if the range is 85-100 or 25-100. In the probabilistic approach, the uncertainty is quantified by the standard deviation.
- The linear transition of a component through a condition state accounts for the effects of aging. The mean value of the CI gradually transitions from the middle of the condition state to the lowest value in the condition state while the standard

deviation remains the same. The component that has been in a given condition state longer will be more likely to receive the maintenance funding.

- The assumptions of components that are statistically independent and normally distributed make the numerical computations quite simple. The methodology is only slightly more complex than the deterministic approach and can easily be done on a spreadsheet as was demonstrated in the example.
- The methodology can be applied to virtually any structure.
- Any relevant variable can be included in the analysis, if one can effectively estimate its relative importance to the rest of the structure. Even variables that are difficult to quantify numerically can be used.
- Even if the initial assumptions are wrong, the data that is needed to correct and update them is the exact data that is being inspected. If the inspections are periodic and relatively frequent, there will be sufficient time to incorporate the actual results and revise the life-cycle maintenance projections for the structure.
- The structural system CI ratings provide an effective means of comparing the relative conditions of structures that are experiencing very different distresses. It is also an excellent means to communicate the condition of the infrastructure in a standardized way for purposes of funding and public safety.

In sum, this approach offers everything that the deterministic approach offers and produces additional benefits. Since there is no additional burden on the inspector, there is no down side to replacing the deterministic procedure with this methodology, despite the fact that it has some limitations.

7.1.2 Limitations

While there are benefits to this methodology, there are also some rather severe limitations that need to be considered and may merit further study.

- This is a probabilistic methodology based on no real data. The definition of failure and the capabilities of the inspectors are both just intelligent guesses. Real data will only come over time based on actual performance. Because there are not that many locks and dams of a similar type, a statistically significant data base may never be available. The hydropower studies by Ayyub *et.al.* (1996) and Mlaker (1994) suffered from a lack of data.
- The assumptions of statistical significance and normal distribution may not be correct. Large portions of distributions for condition states will extend outside the 0-100 range as shown for CS1 and CS4 in Fig. 4.5. Given the inherent limits to the accuracy of this methodology, this will not have a serious effect on the results. The largest errors will apply to those extreme condition states where the component is clearly safe or clearly failed. The more critical issue is that with independent components, the standard deviation of the CI becomes progressively smaller at successively higher levels of the hierarchy. The assumption is not conservative and therefore dangerous. Further study is needed.
- The methodology needs a red flag provision where an independent analysis and conscious repair/no repair decision is needed whenever an inspected item receives a CI score less that 40. Otherwise, analysts who focus on system level CI data will miss minor failures that need to be addressed.
- The system CI proposed here does not follow the rules of traditional system reliability and will therefore be controversial. The traditional system reliability

approach will provide the probability that something in the system will fail. It cannot account for component importance and necessitates an analysis of correlation between failure modes. The system CI proposed here purports to provide the probability that an entire structure will be replaced or rehabilitated. That has not been proven and the distinction will inevitably cause confusion.

- This proposed approach is not a replacement for a traditional reliability analysis. It does not include loads, stresses, deformation, size of fatigue cracks, or moments of inertia that are required for the commonly accepted capacity-demand reliability analysis. We have no idea how a cost-benefit analysis for a given structure using a traditional reliability approach and the approach described here will vary in their results.

7.2 Recommendations

Based on the relative capabilities and limitations discussed in this report, the following recommendations are made for further study and action:

- This report simply outlines a methodology and illustrates it on a sample structure. This study should be continued by applying it to a single type of structure for which CI methods exist such as miter gates, spillways, or hydropower structures. This would determine what procedural modifications are needed between similar structures in different locations. A comparison of inspection results from various structures would provide a common sense assessment of the validity of the methodology. Inspections by actual inspectors will provide the best suggestions for improvement and will either verify or refute the claim that this methodology produces more consistency between inspectors. If previous CI data exists, it could be included in a time-dependent assessment of an actual structure. The analysis of the Great Falls Spillway covered only a point in time. Finally, a traditional reliability analysis and the approach proposed in this report should be done on the same structure and the results should be compared. That might offer insight as to which approach is more appropriate for which situations.

- The methodology appears to be applicable for any type of structure and should therefore, be studied for its applicability to highway bridges, buildings, and other common civil structures.
- The standardization of CI methods for different structures is aided tremendously by using a consistent system where the range of CI values is from 0 to 100 and the general definition of ranges is consistent. Similarly, the concept of a structural hierarchy should be consistent for all structures. The CI procedure for earth and rockfill embankment dams (Andersen *et.al.* 1999), for example, uses a hierarchy to describe the structural system. The procedures for miter gates (Greimann *et.al.* 1990) and sector gates (Greimann *et.al.* 1993) should be revised to incorporate a standardized method.
- Foltz *et.al.* (2001) indicates that CI use throughout the Corps of Engineer districts has been sporadic. Some districts use CI inspections in a half-hearted manner and some do not use them at all. The only way for an effective database to ever be established is for every district to conduct CI inspections on a periodic basis and report the results to a higher headquarters where they can be consolidated,

evaluated and used. The Federal Highway Administration provides an excellent model in its requirements for inspection and reporting of condition on the nation's highway bridges. To repeat the recommendation made in Estes (2003), the Corps of Engineers should make a commitment at the highest level to require all districts to conduct CI inspections and then continually consolidate and the publish the results. The initiative could be phased in over time starting with a specific type of structure. The inevitable bugs could be worked out at a smaller level before incorporating more structures.

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